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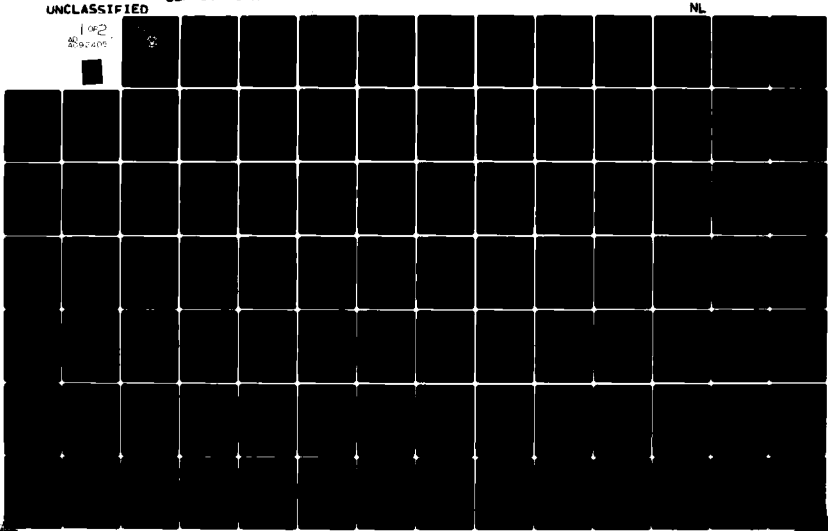

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# THESIS

AN APPLICATION OF MULTIDIMENSIONAL SCALING TO THE PRIORITIZATION OF DECISION AIDS IN THE S-3A

by

Clifford Monroe Cagle

September 1980

Thesis Advisor: W. E. Moroney

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# An Application of Multidimensional Scaling to the *Prioritization of Decision Aids in the* S-3A

by

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Lieutenant, United States Navy
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submitted in partial fulfillment of the requirements for the degree of

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# I. INTRODUCTION

## A. HISTORY

Decision making and the process by which decisions are made in the complex world of Antisubmarine Warfare (ASW) has long confounded the designer as well as the operator of modern sophisticated weapons systems. Operator [Zachary 1980a], software, and hardware [NAVAIR 1975] limitations have been cited as causes of less than optimal performance in the modern ASW mission.

Antisubmarine Warfare has traditionally been thought of as a half science - half art method of locating hostile submerged vessels. Originally, ASW was conducted solely by war ships using active ranging equipment where tactical 'guessing' filled the information gaps left by onboard sensors. As the missions of submarines became more diversified, air and subsurface weapons platforms were developed to augment existing surface weapons systems. With the advent of computers, the information gaps of past sensors narrowed considerably. However, while the operator received more accurate, real time information, the quantity of this new information could, at times, overwhelm even a seasoned operator. To enhance the operator's ability to perform the ASW mission, systems were developed to integrate the large quantity of information, filter the 'noise' from the needed inputs, and present the information in an orderly, useful manner. Such systems were implemented for surface, subsurface, and airborne weapons systems.

## B. ASW MISSION

All ASW weapons systems - airborne, surface, and subsurface - share four basic phases of mission accomplishment: search, localization, track, and attack. The first phase, search, involves the planning and implementation of strategies (sensor placement, areas of search, initial tactics) to gain initial detection of potential threat. In the second phase, the potential threat is localized through the use of additional sensors and detection information. After localization of the potential threat, the third phase, tracking is accomplished by the integration of sensor information and tactics. In peacetime, tracking is the mission priority, while in wartime, the fourth phase, attacking, receives a higher priority. These phases should be followed systematically to assure, in time of peace, constant position information on potential threats, or in time of war, destruction of hostile submarines.

Throughout these four phases, ASW personnel are engaged in decision making tasks of various degrees of complexity and difficulty. Decision aids could be of great use in performing these tasks. Antisubmarine Warfare is a dynamic environment in which one can not train for all possible conditions. Accordingly, emphasis is placed on software, in the form of decision aids, to assist the operator in the performance of the ASW mission. However, decision aids have traditionally been based on designer subjectivity, random fleet inputs, and in response to a new, immediate threat. Regretably, fleet ASW personnel have had little impact on the design and implementation of ASW decision aids. A prioritization of ASW decision areas in which decision aids could be of benefit would directly impact on all ASW assets.

Because of the multitude of ASW platform types in the U.S. Navy, the scope of this thesis was limited to one platform in the accomplishment of the ASW missi( The criterion for selection were (1) an operator whose primary duty is ASW, (2) a 'state-of-the-art' weapons system (hardware and software), and (3) ease of data collection. The S-3A Viking aircraft fulfilled these criteria and was selected as the wearpons platform of interest.

## C. PLATFORM OF INTERESTS

The S-3A Viking, a carrier based, twin engine jet aircraft, with an onboard digital computer, sophisticated avionics and crew of four is considered to be the Carrier Battle Group's first line of defense from hostile submarines. Although the S-3A has other missions, only the ASW mission will be addressed in this thesis. The crew of the S-3A consists of: Pilot, who is responsible for safety of flight; the Copilot, who operates the nonacoustic sensors (Radar, Flir, ESM, and MAD); the Acoustic Sensor Operator (SENSO), who is responsible for passive and active acoustic surveillance; and the Tactical Coordinator (TACCO), who is normally the tactical mission commander and is responsible for the prosecution of subsurface contacts. Because the TACCO receives information from all other members of the crew as well as the onboard General Purpose Digital Computer (GPDC) for his tactical decision making, he will be of primary interest in establishing priority for decision aids. For definitive purposes, a decision aid is any methodology, algorithm, queue, or filtering mechanism that enhances an operator's performance by eliminating unwanted, extranious information and presents critical information in an orderly, streamline fashion to expedite a needed response.

## D. PURPOSE

The purpose of this work was to examine ASW decision making in the S-3A Viking through the use of mathematical modeling techniques and to establish a prioritization technique for the development of decision aids to assist decision making in the S-3A.

## E. ORGANIZATION OF THIS THESIS

The main body of this thesis addresses the results of

Multidimensional Scaling techniques and the resulting applications to decision aids. Chapter 2 discusses the advantages and disadvantages of various scaling methods classified under the general heading of Multidimensional Scaling. The methods evaluated included pairwise comparison, unconstrained sorting (Q-Sort), and the triad method. Chapter 3 discusses the data collection. Chapter 4 contains the data analysis based on the unconstrained sorting technique with emphasis on Unfolding Analysis. Finally, Chapter 5 discusses the results, conclusions, and recommendations.

## II. MULTIDIMENSIONAL SCALING TECHNIQUES

### A. OVERVIEW

ASW decision making, because of the complexity and quantity of information flow, lends itself to few mathematical modeling techniques. ASW decisions, while based on a logical flow of events, are subjective in nature yielding ordinal data points at best.

Few modeling techniques can use data of less than interval nature. However, a family of modeling techniques does exist that use nonmetric (ordinal data) as well as metric (interval or ratio data) inputs. One such group of techniques is Multidimensional Scaling (MDS). Before an application of Multidimensional Scaling can be used to examine ASW decision making, a working understanding of the technique should be attained.

Multidimensional Scaling is the term loosely used to identify a large group of varied and powerful techniques for the analysis of data normally associated with the behavioral sciences. There exist two main purposes for utilizing these techniques - (1) to detect any pattern, structure, or relationship that may be hidden in a matrix of empirical data, and (2) to represent that structure in a form that is intuitively appealing and is more intelligible to the human (i.e. a two or three dimensional graph vice a five or six degree dimensionalization). The stimuli under study are represented by points in this geometric model such that the significant facets of the data points (stimuli) are revealed in their relationship among other stimuli [Shepard 1972].

The spatial representation resembles more traditional relationship scales such as temperature or time in that it attempts to acquire the fundamental properties (structure) of stimuli under study solely by setting them into correspondence with positions within a spatial subset of N dimensionality. It differs from simple unidimensional (i.e. conjoint measurement) scales in that in order to utilize all of the information provided by the data or capture the full complexity of the stimuli, the data points may assume positions within a two, or three dimensional space as well [Kruskal 1978].

In most cases, one seeks a presentation of the model of the lowest possible dimensionality consistent with the problem to be solved and the data. Obviously, a lower dimensional model would be easier to understand intuitively and easier to work with, for it represents the data by means of a smaller number of parameters. Minimizing the number of parameters also yields a more reliable statistical base due to larger data subsets. However, the reduction of dimensionality is not an end unto itself. One runs the risk of damage to the data by arbitrarily reducing the dimensionality of the model. If the relationship among stimuli is sufficiently complex, two or three dimensions, then the model better 'fits' the empirical data. The goodness of fit measurement called 'stress' is the parameter that measures the deviation of the empirical data from the model. There exist a gray area of trade-offs between easy visualization and the use of all data information. It is the analyst's responsibility to execute the trade-off after evaluating the criteria for analyzing the model.

Multidimensional Scaling utilizes the same basic concepts as Factor Analysis. The high dimensionality, usually associated with Factor Analysis, is caused by the rigid assumption of linearity among stimuli. This assumption is relaxed in the model used for Multideminsional Scaling, allowing (normally) a two or three dimensional representation. Essentially, Multidimensional Scaling provides greater stimuli resolution in a more readily visualizable model than Factor Analysis.

Multidimensional Scaling uses similiarities or dissimiliarities among stimuli to define the relationships that exist in each possible dimension. Several subsets of multidimensional scales exist in various forms for different appilcations. The subsets include paired and triad comparisons, unconstrained sorting, conjoint measurement, delphi method, and multiple attribute utility models. However, the major subsets considered in this thesis were limited to pairwise comparison, unconstrained sorting, and triad comparison because of external constraints placed on the data collection. The constraints were the short periods of time available for data collection and the inaccessability of subjects after the initial interview. The constraints will be discussed throughly in Chapter III. Because of the multiple passes required through the data and subject interaction required, the techniques of multiple attribute utility, delphi and conjoint measurement were considered less desirable than the selected techniques.

The measure of effectiveness for the pairwise comparison, unconstrained sort, and triad comparison is how well the model or technique represents the empirical data. This measure of effectiveness is called 'stress' [Kruskal 1978]. Stress is the goodness of fit measurement for the model used to determine the number of dimensions considered, balanced by the amount of deviation from the data. Stress measures the degree of departure from the assumption that there is a monotonic relationship between the non-metric dissimiliarity measures of the data and the metric distance measures of the representational structure [Burton 1968].

## B. PAIRWISE COMPARISON

The most common technique is the pairwise comparison of stimuli with a ranking or weighting between the two [Kruskal 1978]. The pairwise comparison examines N different stimuli in pairs, assigning relative ranks as to the degree of similiarity or dissimiliarity of the two stimuli being compared. The comparisons are used to form matrices of ordinal preference data. The pair-wise data is examined for hidden relationships among three or more stimuli that would not normally come to light in pair-wise preference mapping. These relationships form the dimensionality of the model and point to areas of greatest (or least) interest.

While the pairwise technique utilizes the greatest amount of information from a given set of data, several limitations become apparent in the use of this comparison method. For N stimuli, the number of pair-wise comparisons are $N(N - 1)/2$. For all but a small number of comparisons ($N \leq 10$), the number becomes unmanageable. The complexity increases with larger subject samples. Additionally, the tester normally has a finite time limit and even a small sample (N = 8, subjects = 10) requires a large amount of time.

## C. UNCONSTRAINED SORTING

The unconstrained sorting task [Burton 1975] requires subjects to sort stimuli into groups. The sorting into groups represents a partitioning of the stimuli set. Normally, the stimuli set consist of the stimuli represented in a medium that is easily sorted (such as 3 X 5 cards) and test subjects are asked to sort the stimuli into groups. The instructions for the formation of these groups require the subjects to sort the stimuli that are 'similar in meaning' or 'belong together' into the same group. The subjective interpretation of the sorting instructions by each member is the basis for an unconstrained sort. The subsets (groups) of stimuli can have any number of members. A single stimulus in a group represents no similarity to any other stimulus and all stimuli in a group represent total similarity among stimuli. Test subjects who have few subgroups of stimuli are called 'lumpers' and subjects who make many distinctions among stimuli are referred to as 'slitters'. Burton's study of Q-Sort data [1975] suggest that among Multidimensional Scaling techniques, the unconstrained sorting task is the most flexible in terms of testing procedures.

## D. TRIAD TEST

The triad test is similar in procedure to the paired comparisons discussed earlier except stimuli are compared three vice two at a time. The triads test may be administered in two different ways. The first way requires the subject to choose the most different stimulus from among the three stimuli presented. The second version of the test asks the subject to pick the most different stimulus (as before) and also to pick the pair of stimuli which are most different (one from another) [Burton 1975].

There are $\binom{N}{3}$ or $N(N - 1)(N - 2)/6$ triads for N stimuli. These triads are used to form matrices of ordinal preference data. This ordinal data is monotonically transformed to a metric form that can be examined for relationship or structures that are not apparent at first inspection.

## E. COMPARISON OF TECHNIQUES

Although the pairwise comparison was the most common test found in the literature review [Shepard 1972], [Kruskal 1978], the unconstrained sort and triads test revealed several interesting advantages for the implementation of either technique. The advantages and disadvantages of each technique are discussed in this section.

All three techniques share the advantages of being a simple task to understand and all can be presented either verbally or in written form. At this point, the paired comparision and triads test begin to differ from the constrained sort. For N stimuli and M subjects, the number of pairs presented by the tester is $\binom{N}{2}M$ or $N(N - 1)M/2$ and the number of triads presented equal $\binom{N}{3}M$ or $N(N - 1)(N - 2)M/6$. Intuitively, one can see the advantage of the triads test in the sheer number of stimuli groups. However, for $N \geq 10$ and $M \geq 10$, either test soon becomes unmanageable in terms of time necessary to give the test.

On the other hand, the unconstrained sorting technique has one clear advantage : time. The unconstrained sort can be given to several subjects at once and recent research by Burton [1975] suggests that most people can do a single sorting of sixty(60) stimuli in fifteen to thirty minutes. Additionally, experiments by Miller [1974] indicate that triads test and sorting task uncover the same structure within sorting decisions.

## F. SELECTION OF TECHNIQUE

As discussed in the preceeding sections, each of the three Multidimensional Scaling techniques can be applied to a great number of problem areas with varying degrees of success. An examination of the problem area suggested that one technique was superior to the other two.

The problem concerned the ASW operational decision making environment, specifically the S-3A aircraft. Because of the dynamics of the S-3A environment ashore (Weapons Systems Trainers, ground schools, and training flights), it was essential to interview as many experienced TACCOs as possible in the shortest amount of time so as not to interfere with training and operational commitments. Consequently, with time as the major constraint, the unconstrained sorting technique was selected.

# III. APPLICATION

## A. PROBLEM

The development of air ASW decision aids requires an understanding of the complexities and the interrelationships among decisions of the ASW mission. The measure of importance with respect to ASW decision making is a non-quantifiable variable that directly impacts on priorities among decisions. Because of the subjective nature of ASW decision making, Multidimensional Scaling, in general, and the Unconstrained Sorting Task, specifically, lend themselves favorably to the prioritization of the ASW decision space. An examination of the specific S-3A ASW decision making process was helpful as an overview to the problem.

As mentioned in the introduction, the air ASW mission was divided into four general phases: (1) search, (2) localization, (3) track, and (4) attack. While all of these areas are important, the number of stimuli (phases) concerning the mission was too small to yield any appreciable information about the decision function. An improvement over the four phase model was the repartitioning by Zachary [1980a] of the air ASW decision space into six specific decision situations. The six specific decision situations were:

1) On-station search

2) Contact classification/verification

3) Localization

4) Surveillance tracking

5) Attack planning

6) Lost contact requisition

The six decision situations model, while an improvement over the four phase model, did not remedy the problem of limited information used as input to Multidimensional Scaling models. The six 'phase' model was further evaluated by Zachary [1980b] and found to have varying numbers of constituent decision functions associated with each phase. These constituent decision functions were not considered to be confined to only one decision situation but rather each decision function could be used in any or all combinations of the decision situation (phases) to which that decision function was considered applicable. Table I shows the decision function composition of the six air ASW decision situations.

From a careful examination of the decision situations in Table I, fourteen (14) distinct decision functions emerged as necessary to completely describe the air ASW decision space within the context of this thesis. Consequently, the fourteen decision functions listed in Table II became the stimulus set for the multidimensional scaling sampling. The decision functions and their descriptions are listed in Table II.

Table I. Decision Function Composition of Six Air ASW Decision Functions

| DECISION SITUATION | CONSTITUENT DECISION FUNCTIONS |
|---|---|
| ON-STATION SEARCH | CREATE SENSOR PATTERN<br>MANAGE EQUIPMENT/STORES<br>EXTEND SENSOR PATTERN<br>ADJUST PATTERN TO SENSOR FAILURE<br>CONSTRUCT SENSOR MONITORING PATTERN<br>COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS |
| CONTACT CLASSIFICATION/VERIFICATION | CLASSIFY SIGNAL<br>DETERMINE SIGNAL IS A VALID CONTACT |
| LOCALIZATION | MANAGE EQUIPMENT/STORES<br>ANTICIPATE TARGET MOVEMENT<br>EXTEND SENSOR PATTERN<br>GAIN ATTACK CRITERIA<br>DETERMINE TARGET FIX<br>COORDINATE HAND-OFF<br>ADJUST PATTERN TO SENSOR FAILURE<br>CONSTRUCT SENSOR MONITORING PATTERN<br>COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS |
| SURVEILLANCE TRACKING | CREATE SENSOR PATTERN<br>MANAGE EQUIPMENT/STORES<br>ANTICIPATE TARGET MOVEMENT<br>EXTEND SENSOR PATTERN<br>DETERMINE TARGET FIX<br>COORDINATE HAND-OFF<br>ADJUST PATTERN TO SENSOR FAILURE<br>CONSTRUCT SENSOR MONITORING PATTERN<br>COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS |
| ATTACK PLANNING | CREATE SENSOR PATTERN<br>MANAGE EQUIPMENT/STORES<br>ANTICIPATE TARGET MOVEMENT<br>EXTEND SENSOR PATTERN<br>GAIN ATTACK CRITERIA<br>DETERMINE TARGET FIX<br>ADJUST PATTERN TO SENSOR FAILURE<br>DETERMINE WEAPON AND SETTING FOR ATTACK<br>CONSTRUCT SENSOR MONITORING PATTERN<br>DETERMINE AIRCRAFT WEAPON LAUNCH POSITION<br>COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS |
| LOST CONTACT REACQUISITION | CREATE SENSOR PATTERN<br>MANAGE EQUIPMENT/STORES<br>ANTICIPATE TARGET MOVEMENT<br>EXTEND SENSOR PATTERN<br>COORDINATE HAND-OFF<br>ADJUST PATTERN TO SENSOR FAILURE<br>CONSTRUCT SENSOR MONITORING PATTERN<br>COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS |

Table II. Description of the Fourteen Decision Functions

- ADJUST PATTERN TO SENSOR FAILURE (AP) - replacement of faulty sensors or adjustment of aircraft track due to requipment/sensor failure.

- EXTEND EXISTING SENSOR PATTERN (EP) - determine orientation and settings of sensors to be added to existing pattern with no contact.

- ANTICIPATE TARGET MOVEMENT (AM) - predict future location, course, speed, and depth of target based on intelligence and actual tactical situation.

- CONSTRUCT SENSOR MONITORING PATTERN (MP) - determine where to position the aircraft to obtain maximum reception from sensors, and sequence in which to monitor deployed (acoustic) sensors if number of sensors exceeds number of aircraft receivers.

- COORDINATE HAND-OFF (CH) - transmission of data to relief platform for continuation of prosecution.

- DETERMINE SIGNAL IS A VALID CONTACT (VC) - reduce false alarm rates of sensor system (e.g., clouds on radar, random noise on MAD or acoustic).

- DETERMINE WEAPON AND SETTING FOR ATTACK (DS) - select weapon to be used for the attack, and its optimum weapon settings (e.g., search depth, minimum/maximum search limit).

- GAIN ATTACK CRITERIA (AC) - interpret sensor data to determine when target is localized sufficently to place an attack.

- DETERMINE TARGET FIX (TF)- use incoming sensor data to establish the location of the target.

- CREATE SENSOR PATTERN (CP) - determine pattern, spacing, orientation and/or utilization for all sensor types for each phase of the mission.

- MANAGE EQUIPMENT/STORES TO ACCOMODATE PRESENT AND FUTURE NEEDS (ME) - monitor inventory of sensors and equipment status for application for future tactics and resources.

Table II. Continued

- CLASSIFY SIGNAL (CS) - determine if signal (primarily acoustic) may be originating from the target of interest.

- COMPENSATE FOR ACOUSTIC/ATMOSPHERIC PROPAGATION CONDITIONS (PC) - determine the adjustments in sensor spacing, aircraft track, aircraft altitude, etc., that must be made when actual (in situation) atmospheric and bathythermal conditions are different from their forecast.

- DETERMINE AIRCRAFT WEAPON LAUNCH POSITION (LP) - determine factors to place the aircraft in an optimum attack position.

In this analysis, the TACCOs were asked to perform two psychometric tasks to elicit indicators as to the subjective nature of ASW decision making. The first task was an unconstrained sorting of the stimulus set of 14 decision functions that provided the necessary inputs for the Multidimensional Scaling. The second task was a set of rank orderings of the stimulus set that provided inputs to the unfolding analysis and the correlations testing. Both task will be discussed in detail in the following sections.

1. Unconstrained Sorting Task

The technique of the unconstrained sorting, also know as the 'Q-sort', was first developed by Stephenson [1953]. The technique was further refined by Burton [1968] and applications of the scaling were validated by Miller [1974]. In this task, the subject is asked to partition the members of the stimulus set into an arbitrary number of groups of unspecified size. The criterion for sorting usually is a similarity or dissimiliarity judgement by the subject established by the instructions for the task. There is no limit on the number of stimuli in a group nor is there a limit on the number of groups.

As discussed in the previous chapter, the unconstrained sorting task is only one of many psychometric methods used to collect data for Multidimensional Scaling. Unconstrained sorting was chosen over the other discussed techniques for two reasons. First, the unconstrained sort allows the levels of discrimination among the stimuli by each subject to be controlled for explicitly in the processing of the results. Subjects will place varying degrees of emphasis on the underlying structure of the interrelationships among stimuli. The algorithms developed for this technique in the processing of data inputs control for between subject variance. Subjects, however, vary widely in the level of detail perceived to be necessary for performance of the sorting task. The perceived level of detail task performance can differentiate broad distinctions that find all stimuli very much alike or very different; or from very few distinctions that find small groups of stimuli similiar but in different degrees. Depending on the degree of distinction required by the interviewer, the instructions must be expressed so as to focus on a specific level of distinction required of a scaling task. This is the primary reason for choosing the unconstrained sorting task.

Secondly, the unconstrained sort is the simplest, most expeditious method of collecting data for Multidimensional Scaling. As discussed in the previous chapter, the limited amount of time available for TACCO interviews was critical. The sorting task portion of the interview took less than 30 minutes for each TACCO, favoring this technique over more time consuming methods.

Thorough investigation of Burton [1968], Miller [1974] and Zachary [1980b] have shown that unconstrained sorting produces equivalent results to the other MDS techniques when two general rules of thumb are obeyed. The first rule is that the number of stimuli must be greater than ten, ($S > 10$), and second, there must be at least twice as many subjects (N) performing the sort as there are stimuli, ($N \geq 2S$). The fourteen decision functions, previously discussed, meet the stimuli number requirement and a total of 30 S-3A TACCOs interviewed satisfied the second condition.

Each TACCO interviewed was presented the sorting task stimuli verbally, in the briefing, and in writing, in the form of a deck of 3X5 inch index cards. The written and the verbal presentations were identical in nature. In the center of each stimulus card (in bold print) was the name of the decision. Following the name was a brief explanation of the decision function. To identify each stimulus card, a two letter code was used (in the upper right corner) to record the sorting response as well as the ranking (to be discussed later). Figure 1 represents a sample decision card used in the interviews. The codes were mnemonic in nature, derived from the keywords of the decrision functions. Table II lists the codes and the decision functions used in the data collection. Mnemonic codes were selected instead of numeric or alphabetic codes to eliminate any bias in the way the cards were sorted due to any unintentional implicit ordering.

Figure 1. Sample Decision Function Card

---

AM

ANTICIPATE TARGET MOVEMENT

predict future location, course, speed, and depth of target based on intelligence and actual tactical situation

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2. Ranking Task

The second psychometric task performed by the TACCOs was a rank ordering task. The subjects used the stimulus cards, discussed previously, and ranked the stimuli according to four different criteria. The criteria for the four rankings were:

1) Importance of the decision in the ASW mission with an attack on a submarine.

2) Importance of the decision in the ASW mission with only surveillance of a submarine.

3) Urgency of the decision, and

4) TACCO workload during the decision.

Rankings 1 and 2 provided inputs for the Unfolding Analysis (discussed in Chapter IV). They were selected for the Unfolding Analysis because they use the same criterion - importance of the decision to the accomplishment of mission - but under different circumstances - attack versus surveillance. This difference was used as a reference. The criterion of importance was defined as the degree to which a less than optimal decision would adversely impact on the achievement of the mission objective.

Urgency, the third ranking criterion, was defined as the relative speed with which the decision had to be made, at a decision point. The fourth ranking criterion, workload, was defined only in the most general terms. Each TACCO was instructed to consider mental as well as physical workload. These last two rankings were used to provide supplemental information which could aid in the interpretation of the MDS solution.

## B. DATA COLLECTION

This thesis is based on the assumption that a priorization of the S-3A ASW decision space must include the knowledge, opinion, and intuition of experienced S-3A ASW decision makers (TACCOs). Multidimensional Scaling and Unfolding Analysis, discussed in the data analysis section of this thesis, provided a way for numerically prioritizing the fourteen decision functions previously discussed, on the basis of structured but subjective inputs from S-3A TACCOs.

The primary source of experienced S-3A TACCO's for this analysis was VSWING 1, NAS Cecil Field, Jacksonville, Florida. For data collection purposes, an experienced TACCO was defined as an individual who had been designated an S-3A TACCO for at least one year or had made at least one deployment as a qualified S-3A TACCO. VSWING 1 was selected as the sample TACCO population primarily because of the availability of experienced TACCOs during the limited time frame of the data collection effort.

The structure of the Multidimensional Scaling interview consisted of three general parts: 1) initial briefing and explanation, 2)sorting task, and 3) ranking task. At the conclusion of the interview an open-ended discussion of decision aids and decision making was held at the interviewee's option. The interview was designed to allow several TACCO's to be interviewed simultaneously but conversation between TACCOs was prevented. The interviews were designed to be completed in a two hour period, as to minimize sample bias due to interviewee fatigue and to minimize work time loss. The designed schedule was as follows:

- 30 minutes were allowed for initial briefing and answering questions
- 20 minutes were allocated for the psychometric sorting task
- 40 minutes were allocated for the psychometric ranking task
- 30 minutes were used to discuss the interview and suggested improvements in the area of decision aids.

It should be noted that the TACCO's interviewed demonstrated an active interest in providing fleet inputs to an area many believed to be critical to the successful accomplishment of the S-3A ASW mission.

At the start of each interview, an initial briefing and explanation was given, outlining air ASW history, purpose of the interview and the possible impact of decision prioritization on the implementation of the future decision aids in the S-3A. Questions were then answered and the interviewees were introduced to the two tasks they were to perform. Portions of the briefing are found in Appendix A.

The actual data collection effort for the sorting and ranking tasks were performed as follows. After the briefing, each TACCO was given a pack of cards (similiar to Figure 1) and a set of response forms (reproduced in Appendix B). The cover sheet of the response form requested background information on each TACCO but the name was purposely left off. The absence of names from the response forms preserved anonimity, hopefully leading to less biased responses. The background information allowed the interview to insure the requirement of experience and training were met prior to inclusion in the test sample. Each task had an instruction sheet preceeding each response form, explaining the required task once again. The unconstrained sort used perceived similiarities among stimuli as the criterion for group partitioning. The four ranking task used the criterion discussed previously. Individual questions during the task were discouraged to decrease any answer interpretation bias. All subjects finished the sorting task in less than 15 minutes, while the rankings, normally, required 10 minutes per task.

Following the last ranking task, each TACCO had an opportunity to comment, regarding ASW decision aids in general, and S-3A decision aids in particular. Comments were solicited concerning the interview (new ideas, format, procedure) and are discussed in the Result and Conclusion sections of this thesis.

# IV. DATA ANALYSIS

## A. OVERVIEW

Chapter Four describes the data analysis for this effort. Initially, the sorting data was preprocessed using Burton's [1975] algorithm into a dissimiliariity matrix to be used as input into the MDS program. The ranking data was analyzed through the use of correlation techniques and average rankings were found. The dissimiliarity matrix was then input into the MDS program and a dimensional representation of the decision space was produced. Dimensional interpretations were derived. Next, Unfolding Analysis was used to provide a representative model of the ranking decision space. Finally, a priority scale of the decision space was established using the model coefficients of the Unfolding Analysis and the Multidimensional Scaling coordinates. Figure 2 provides an overview of this methodology.

## B. PRELIMINARY ANALYSIS

### 1. Preprocessing of Sorting Data

Sorting data were obtained from 32 experienced S-3A TACCOs, however, two TACCOs were excluded because they did not have the experience level required for the analysis. The remaining 30 TACCOs were determined to be 'experienced' for

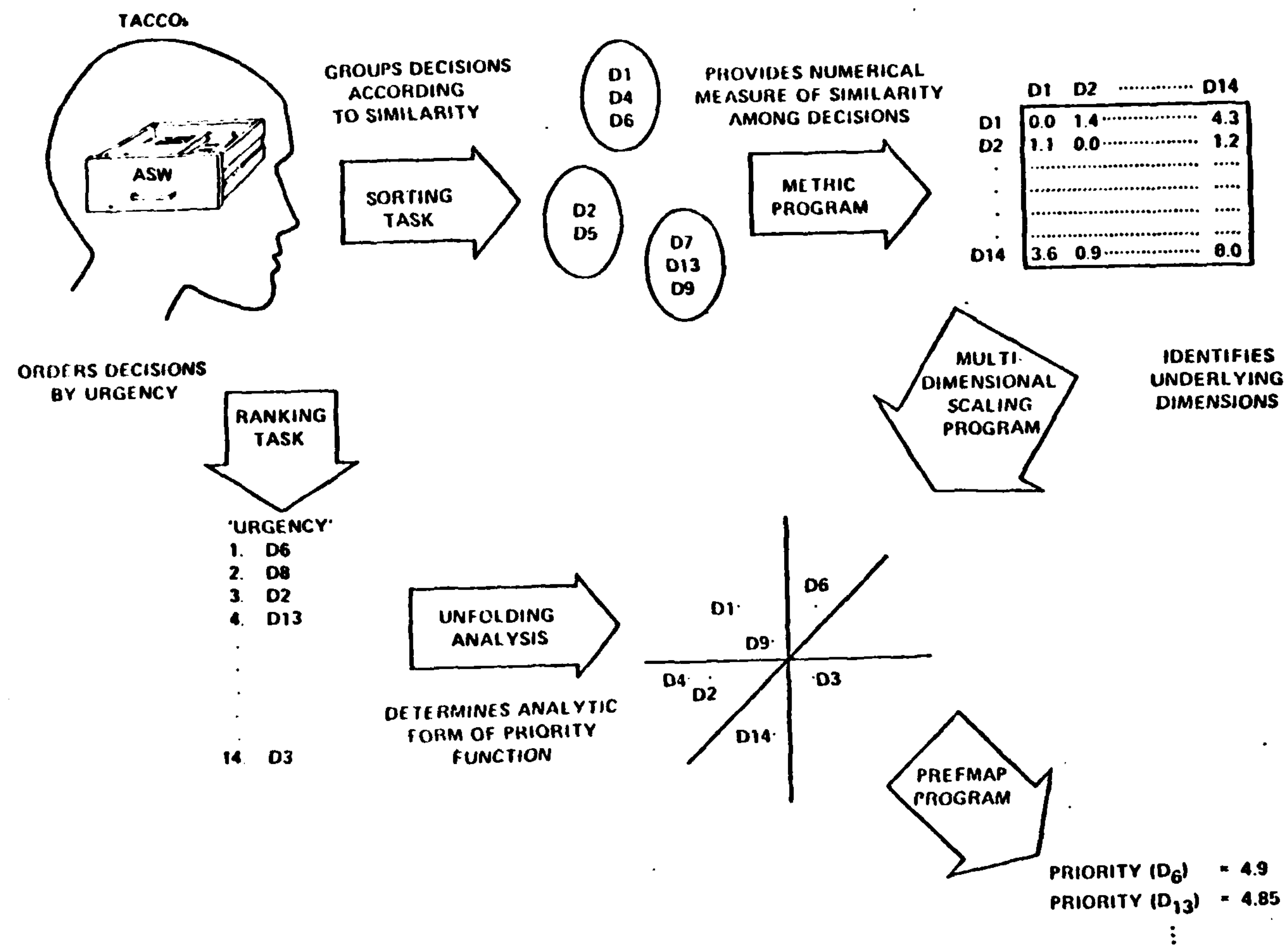


Figure 2. Multidimensional Scaling Prioritization Procedure (adapted from Zachary 1980b)

the purposes of this analysis. These 30 sortings are listed in Appendix C. The 30 sets of data were prepared for input into the MDS computer program by METRIC, an algorithm developed by Burton (1975). The algorithm processes the unconstrained sorting data to produce a dissimiliarity measure among the decision functions in the stimulus set [Zachary 1980b]. In general, a dissimiliarity measure is a binary mapping from the set of objects scaled to some numerical scale. For any two objects i and j, the dissimiliarity between i and j is expressed as $d_{ij}$. Dissimiliarity measures has three main properties:

1) $d_{ij} = 0$ iff: i=j : positivity

   $d_{ij} > 0$ otherwise

2) $d_{ij} = d_{ij}$ *for all i, j : symmetry*

3) $d_{ij} \leq d_{ij} + d_{jk}$ for all i, j, k : triangle inequality.

Dissimiliarity measures are normally represented as a square matrix where each row/column represents one of the stimuli. Consequently, the terms dissimiliarity 'measure' and dissimiliarity 'matrix' are use throughout the analysis interchangeably.

Burton's algorithm computes dissimiliarity between two stimuli based on two inputs:

1) the number of subjects who place them in different groups, and

2) the values assigned to the parameters $\alpha$ and $\epsilon$ .

The first parameter, $\alpha$ , represents the level of discrimination selected for this analysis (as discussed in Chapter III). The parameter, $\epsilon$ , represents the minimal dissimiliarity between two stimuli that results when two stimuli are placed in the same group by one subject. The algorithm is based on the principle that each subject infers a partition on the set of stimuli. $R_i$ is defined as the number of groups formed by subject i and $M_k$ is defined as the number of stimuli placed in group k by subject i. If the number of subjects is T, then dissimiliarity between stimuli x and y is:

$$d_{xy} = \sum (C - S_i (x, y))$$

where:

$$S_i(x, y) = \begin{cases} A_{ik} & \text{if subject i places stimuli x and y in cell k of the partition,} \\ B_i & \text{if subject i places stimuli x and y in different cells of the partition, and} \\ C & \text{if } x = y. \end{cases}$$

d(x, y) is a measure of dissimiliarity which, in addition, is a metric [Burton 1975]. There are two constraints on d:

1) $B_i < \min (A_{ik})$ over all k

2) $C > \max(A_{ik})$ over all i, k

Additionally, a useful measure is obtained by defining:

$$A_{ik} = (M_{ik})$$

$$B_{ik} = 0$$

$$C = \begin{cases} 1 + \epsilon & \text{for } \alpha = 0 \\ N + \epsilon & \text{for } \alpha > 0 \\ 2 + \epsilon & \text{for } \alpha < 0 \end{cases}$$

Since epsilon ( $\epsilon$ ) is a minimum value used to differentiate items placed together by a given subject, it should be very small. Alpha ( $\alpha$ ) represents the level of distinction used by the TACCO doing the sorting. If alpha is greater than zero ( $\alpha > 0$), a greater weight is given to sortings that use a few, large cells, and the distance measure tends to be the lower dimensionality when subjected to Multidimensional Scaling. When alpha is less than zero ( $\alpha < 0$), a greater weight is given to partitions which include a greater number of small cells, and the measure results in higher dimensional MDS solutions. When alpha equals zero ( $\alpha = 0$), equal weight is given large and small cell partitions, as 1 is always added to d(x,y) whenever x and y are in different cells, and epsilon is added to d(x,y) when they are place in the same cell.

The program, METRIC, performs this algorithm to produce a dissimiliarity matrix from the unconstrained sorting. Because the intent of this thesis is to identify the most important dimensions vice all dimensions, an alpha value of -.5 was used. The dissimiliarity matrix is shown in Table III.

2. Preliminary Analysis of Rankings

The rankings of the 14 decision functions by the four criteria discussed in Chapter 3 are given in Appendix D for all 30 TACCOs. The requirement of the preprocessing of data, necessary in the sorting data, was not considered necessary for input into the Unfolding Analysis procedure. However, two preliminary analyses of the ranking data were considered useful to the overall analysis.

The first preliminary analysis tested the statistical significance of the ranking data. The Kendall coefficient of concordance : W is a statistic which measures the relation (degree of agreement) among several rankings of the same set of stimuli [Seigal 1956]. The coefficient of concordance is an index of the divergence of the actual agreement shown in the data from the maximum possible (perfect) agreement. A test of significance of the coefficient can be based on the value of W [Kendall, 1962]. This test is based on the fact that K(N - 1)W is distributed according to the Chi-Square distribution with N - 1 degrees of freedom (where K is the number of rankers and N is the number of stimuli). The null hypothesis, $H_o$, and the alternate hypothesis $H_1$ used were:

Table III. Dissimiliarity Matrix

| | AP | EP | AM | MP | CH | VC | DS | AC | TF | CP | ME | CS | PC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EP | 13.861 | | | | | | | | | | | | |
| AM | 21.603 | 21.155 | | | | | | | | | | | |
| MP | 13.198 | 13.044 | 20.578 | | | | | | | | | | |
| CH | 21.456 | 21.956 | 21.956 | 21.956 | | | | | | | | | |
| VC | 21.956 | 21.956 | 21.956 | 21.956 | 21.956 | | | | | | | | |
| DS | 21.456 | 21.509 | 17.720 | 21.509 | 21.456 | 21.956 | | | | | | | |
| AC | 21.956 | 21.956 | 15.065 | 21.956 | 21.956 | 21.956 | 10.662 | | | | | | |
| TF | 21.025 | 21.603 | 9.141 | 21.603 | 21.956 | 18.492 | 19.667 | 16.565 | | | | | |
| CP | 14.776 | 10.345 | 20.131 | 11.174 | 21.956 | 21.956 | 21.509 | 21.509 | 21.155 | | | | |
| ME | 13.654 | 19.878 | 21.603 | 16.223 | 21.456 | 21.956 | 21.456 | 21.956 | 21.603 | 18.378 | | | |
| CS | 21.379 | 21.956 | 21.956 | 21.956 | 21.956 | 3.902 | 21.956 | 21.956 | 17.915 | 21.956 | 21.956 | | |
| PC | 14.052 | 13.792 | 21.509 | 13.706 | 21.956 | 20.094 | 21.956 | 21.509 | 21.509 | 14.259 | 17.077 | 20.801 | |
| LP | 21.603 | 21.603 | 16.814 | 20.895 | 21.956 | 21.956 | 9.747 | 8.955 | 18.314 | 21.603 | 21.603 | 21.956 | 21.956 |

KEY

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$H_0$ : there is no agreement among the subject's rankings (i.e. $W = 0$).

$H_1$ : there is significant agreement among the subject's rankings (i.e. $W > 0$).

Table IV lists the coefficient of concordance : W, the $X^2$ statistic, and the level of significance for each of the four rankings. All four rankings were found to be significant at less than the .01 level, rejecting the null hypothesis with greater than 99 percent confidence. The significance testing indicates that:

1) the TACCOs used the same criterion for ranking, and

2) the response were not of a random nature.

The second preliminary analysis of the rankings provided insight into the interpretation of each criterion (i.e. 1)importance to mission with attack, 2)importance to mission without attack, 3)urgency, and 4)workload). Average rankings were used as a tool for this analysis. Siegal [1956] and Kendall [1962] suggest that the best estimate of the 'true' ranking of N objects is provided, when W is significant, by the order of the various sums of the ranks. An extention of this estimate is the average ranking. Average rankings yield more information about relative ranking among stimuli than does the sum of ranks [Zachary 1980b]. The average rankings are shown in Tables V through VIII. The tables show a significantly different ranking for each criterion, verifying the assumption that more than one criterion was necessary to capture the implicit prioritization of the decision functions by the TACCOs.

Table IV. Significance of Subject Agreement in Ranking

| RANKING CRITERION | KENDALL COEFFICIENT | CHI-SQUARE STATISTIC | SIGNIFICANCE LEVEL (FOR REJECTION OF $H_o$) |
|---|---|---|---|
| IMPORTANCE WITH ATTACK | .382 | 148.79 | < .001 |
| IMPORTANCE WITHOUT ATTACK | .468 | 182.56 | < .001 |
| URGENCY | .558 | 217.62 | < .001 |
| WORKLOAD | .243 | 94.80 | < .001 |

Table V. Average Ranking of Decision in Mission With Attack

| | |
|---|---|
| Gain Attack Criteria | 3.866 |
| Classify Signal | 4.700 |
| Determine Tarrget Fix | 5.400 |
| Determine Aircraft Weapon Launch Position | 5.433 |
| Determine Weapons Setting For Attack | 5.800 |
| Anticipate Target Movement | 6.200 |
| Determine Signal Is Valid Contact | 6.566 |
| Create Sensor Pattern | 6.600 |
| Compensate For Propagation Conditions | 8.500 |
| Construct Sensor Monitoring Pattern | 8.666 |
| Extend Sensor Pattern | 10.033 |
| Manage Equipment and Stores | 10.200 |
| Adjust Pattern to Sensor Failure | 10.566 |
| Coordinate Hand-Off | 12.533 |

Table VI. Average Ranking of Decision in Mission Without Attack

| | |
|---|---|
| Classify Signal | 3.900 |
| Anticipate Target Movement | 4.966 |
| Create Sensor Pattern | 5.066 |
| Determine Signal Is Valid Contact | 5.166 |
| Determine Target Fix | 5.266 |
| Coordinate Hand-Off | 5.666 |
| Compensate For Propagation Conditions | 6.500 |
| Construct Sensor Monitoring Pattern | 7.233 |
| Manage Equipment and Stores | 7.766 |
| Extend Sensor Pattern | 8.366 |
| Adjust Pattern to Sensor Failure | 8.733 |
| Gain Atack Criteria | 10.600 |
| Determine Aircraft Weapon Launch Position | 13.033 |
| Determine Weapon and Setting For Attack | 13.066 |

Table VII. Average Ranking of Decision by Urgency

| | |
|---|---|
| Determine Aircraft Weapon Launch Position | 2.666 |
| Gain Attack Criteria | 2.933 |
| Determine Weapon and Setting For Attack | 4.800 |
| Anticipate Target Movement | 5.266 |
| Determine Target Fix | 5.333 |
| Determine Signal Is Valid Contact | 5.766 |
| Classify Signal | 6.866 |
| Adjust Pattern to Sensor Failure | 8.400 |
| Manage Equipment and Stores | 9.366 |
| Compensate For Propagation Conditions | 9.900 |
| Extend Sensor Pattern | 10.266 |
| Create Sensor Pattern | 10.666 |
| Coordinate Hand-Off | 11.366 |
| Construct Sensor Monitoring Pattern | 11.933 |

Table VIII. Average Ranking of Decision by Workload

| | |
|---|---|
| Gain Attack Criteria | 4.266 |
| Determine Target Fix | 4.733 |
| Anticipate Target Movement | 5.333 |
| Determine Aircraft Weapon Launch Position | 5.566 |
| Determine Weapon and Setting For Attack | 6.500 |
| Coordinate Hand-Off | 7.000 |
| Create Sensor Pattern | 7.300 |
| Manage Equipment and Stores | 7.600 |
| Extend Sensor Pattern | 8.166 |
| Adjust Pattern to Sensor Failure | 8.633 |
| Compensate For Propagation Conditions | 9.100 |
| Construct Sensor Monitoring Pattern | 10.166 |
| Determine Signal Is Valid Contact | 10.333 |
| Classify Signal | 10.333 |

## C. APPLICATION OF MDS ALGORITHM

The dissimiliarity matrix discussed in the preliminary analysis was the primary input to a MDS program. The analysis was conducted on the University of Pennsylvania Wharton School's DEC-10 computer using the MDSX package of Multidimensional Scaling programs [Coxon et al 1977]. This package contains several different algorithms including the MINASSA algorithm [Lingoes and Roskam 1975], the INDSCAL algorithm [Carrol and Chang 1970] and the TORSCA IV algorithm [Young 1968]. Zachary [1980b] used each of these algorithms on similar ASW data to test for convergent validity among the programs, resulting in virtually identical solutions. Therefore, in the dimensional and prioritization analysis, the MINASSA algorithm was used because the other two algorithms are quasi-metric, whereas MINASSA is totally nonmetric, that is, useful in analysing ordinal data.

The MINASSA algorithm was used to construct solutions from one to five dimensions. The plot of the goodness of fit measure 'stress' versus dimension number, shown in Figure 3, indicates that a three dimensional solution is best. Kruskal [1978] suggest that if the number of stimuli considered, N, is greater than four times the dimension number, D, then a stress measurement of .02 or less is considered a very good fit. Additionally, Roskam's [1977]

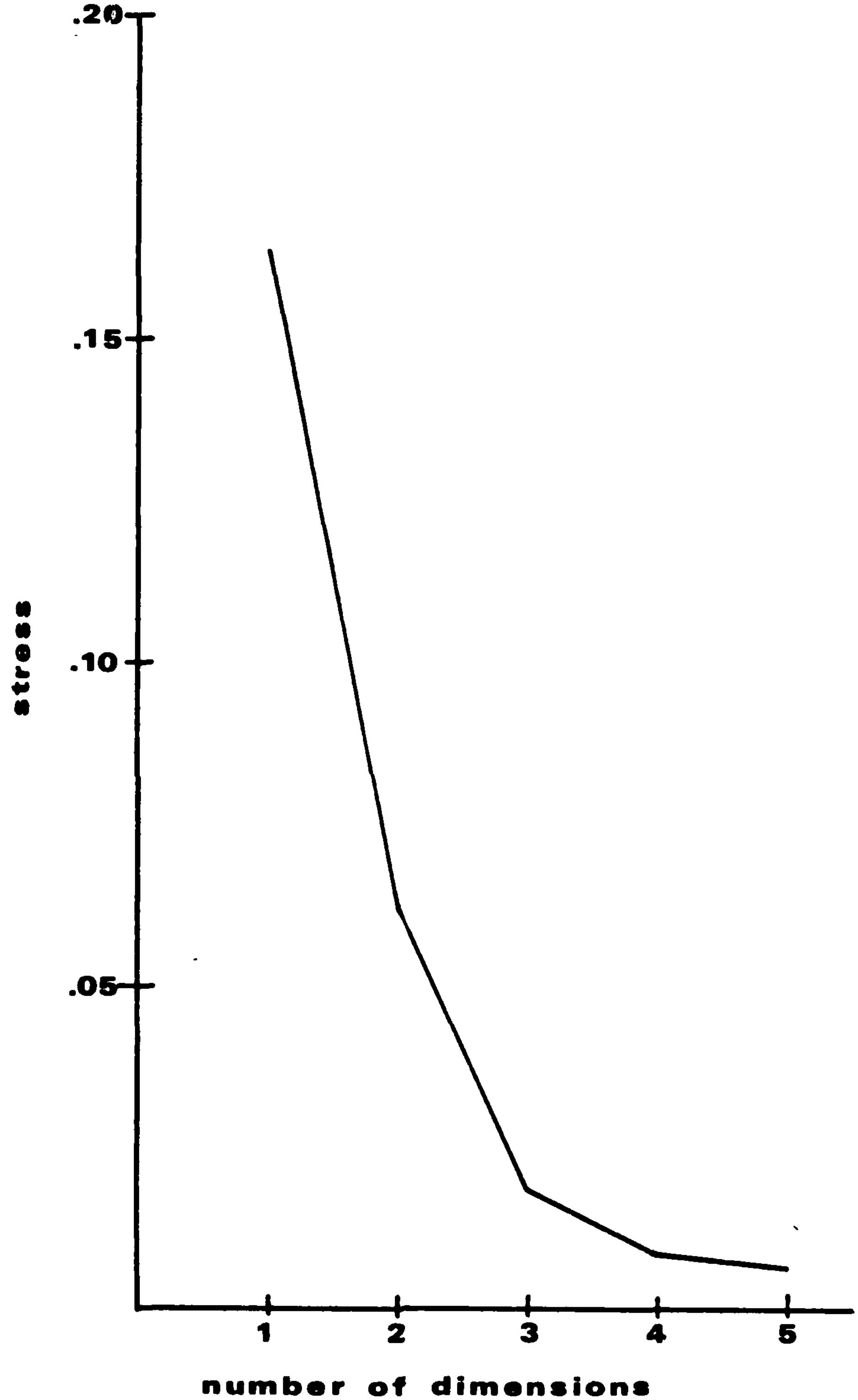


Figure 3. MDS Stress vs. Dimensionality

'rule-of-thumb' for assessing the stress of a MINASSA solution indicates that a stress between .05 and .01 is considered very good quality. Therefore, with a stress of .018, the three dimensional solution satifies the stress requirement for a good fitting model. Although the 4th and 5th dimensional solutions also provide stress measurements less than .02, the incresed complexity of the solutions due to higher dimensionality did not merit further consideration.

The three dimensional solution is shown in Figure 4. For ease of interpretation, two dimensional plots of each possible pair of dimensions are given in Figures 5 through 7. The plots represent relative locations in two dimensions of each of the 14 decision functions. Table IX shows the actual coordinates of each decision function in three dimensions.

## D. DIMENSIONAL INTERPRETATION

The MINASSA algorithm reconstructs the underlying features of relationships of the decision functions as the dimensional axes of the MDS solution. Unfortunately, the algorithm cannot identify the meaning of these dimensional axes. The meanings of the axes must be interpreted through careful examination of the axes individually, through unidimensional projection of each coordinate set, and the interaction of the axes. The unidimensional projections are shown in Figures 8 through 10.

The multidimensional representation constructed by MINASSA is unique and translation or rotation of the axes used to obtain a more interpretable set of projections did not change the relationship among sitmuli. However, the interpretations of the dimensions, discuss subsequently, are based on the 'unrotated - untranslated' spatial representations given in Figures 5 through 7. The basis for this representation is two-fold. First, the MINASSA solution is based on an implicit rotation performed by the algorithm to minimize dependence among dimensions. The orientation of the dimension axes provided the most independent representation in terms of the set of decision functions. Consequently, the independent nature of the resulting axes enhanced the interpretability of the dimensions. Secondly, a rotation and translation of the axis was attempted to provide a more interpretable representation. This analysis did not add to the interpretability of the spatial representation. Additionally, because the unrotated orientations is based on the criterion of minimizing the interdimensional correlation, the original MINASSA result is used in the following interpretation.

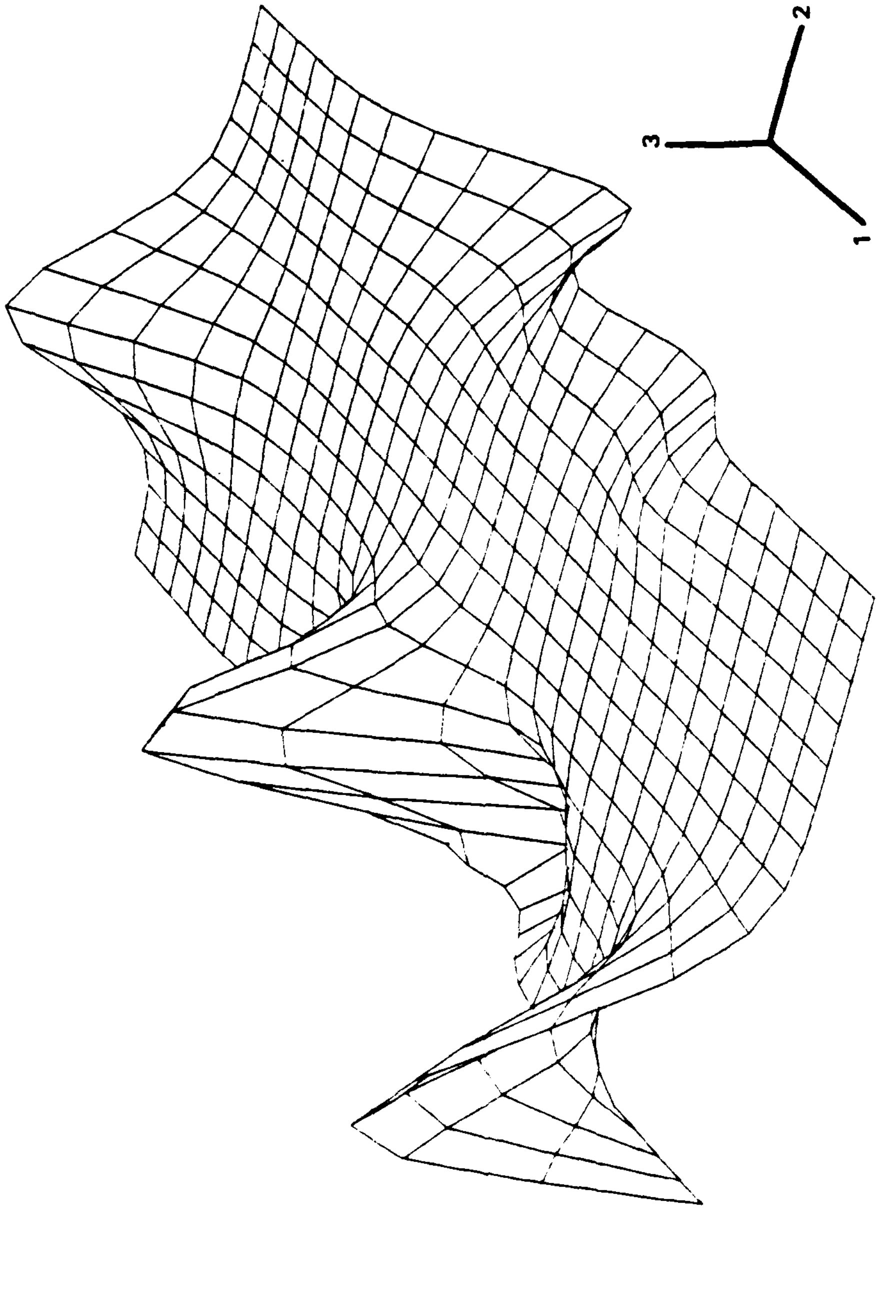
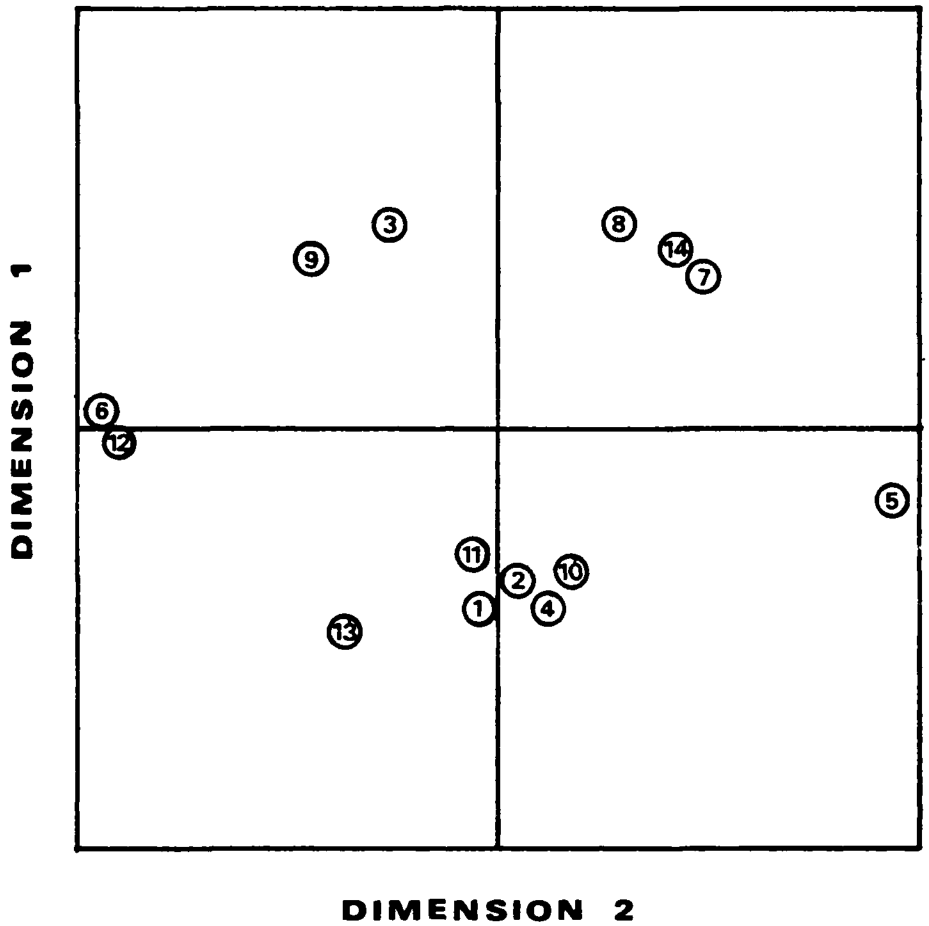



Figure 4. Three Dimensional MDS Plot




KEY
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2. EXTEND SENSOR PATTERN
3. ANTICIPATE TARGET MOVEMENT
4. CONSTRUCT SENSOR MONITORING PATTERN
5. COORDINATE HAND-OFF
6. DETERMINE SIGNAL IS VALID CONTACT
7. DETERMINE WEAPON AND SETTING FOR ATTACK
8. GAIN ATTACK CRITERIA
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11. MANAGE EQUIPMENT/STORES
12. CLASSIFY SIGNAL
13. COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS
14. DETERMINE AIRCRAFT WEAPON LAUNCH POISITON

Figure 5. Dimension 1 vs Dimension 2

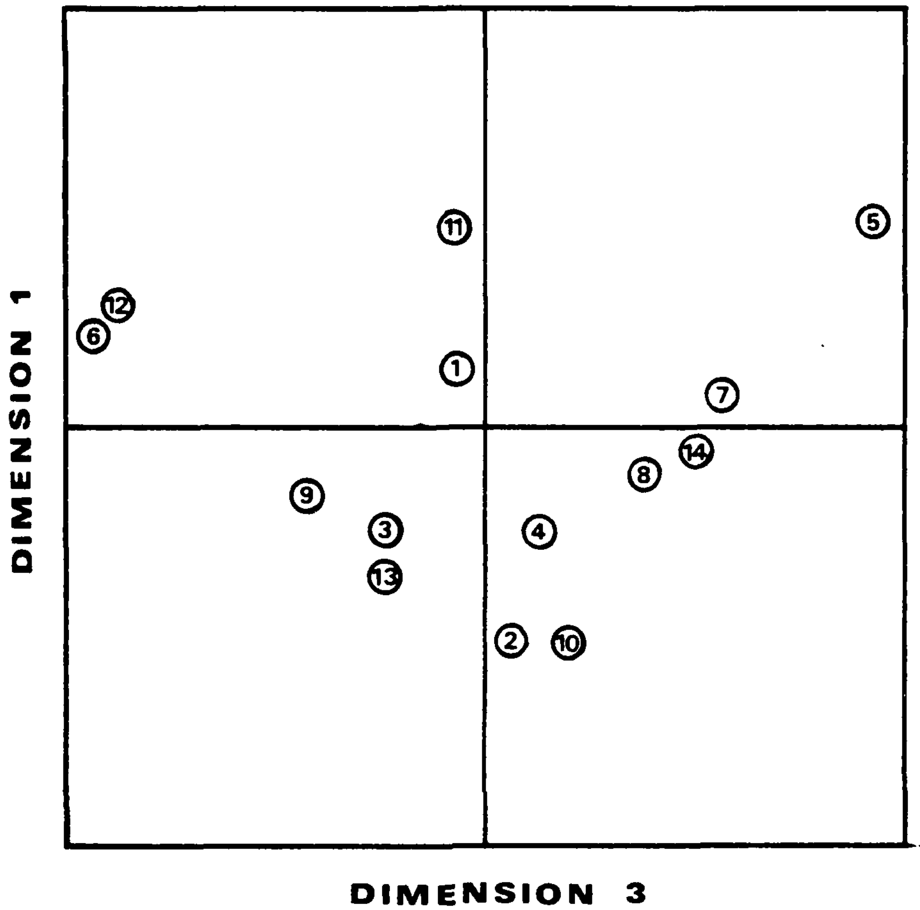


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Figure 6. Dimension 1 vs Dimension 3

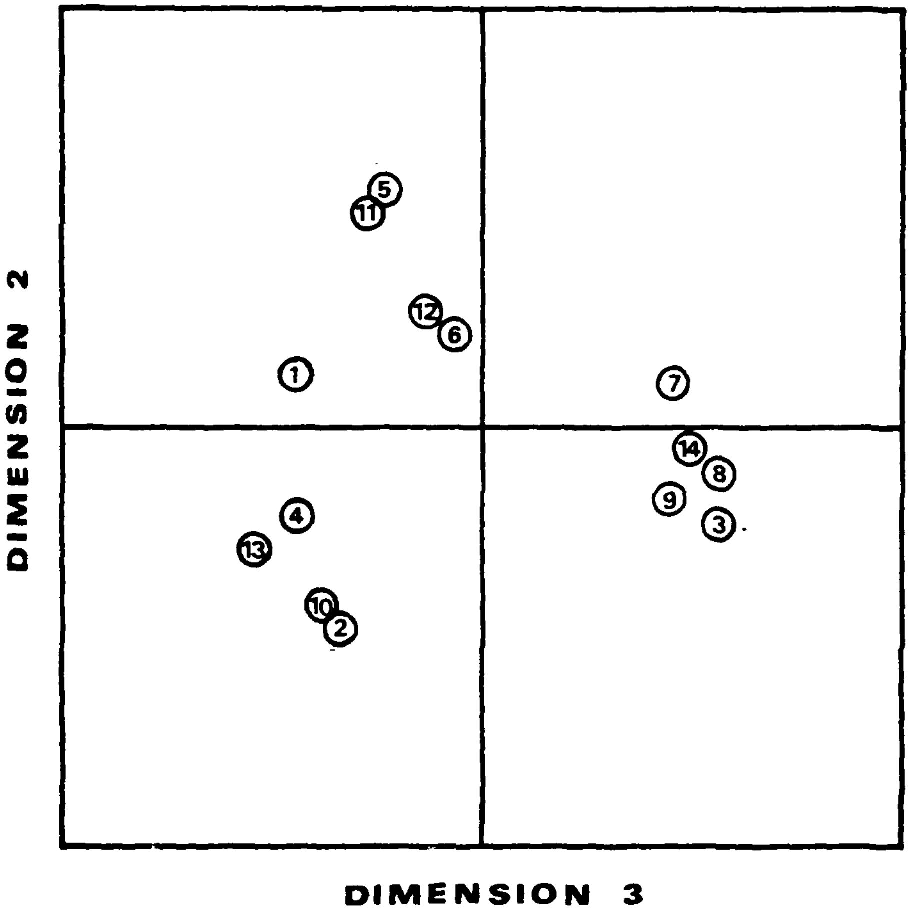


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Figure 7. Dimension 2 vs Dimension 3

Table IX. Final Multidimensional Scaling Coordinates

| | Dimension 1 | Dimension 2 | Dimension 3 |
|---|---|---|---|
| Adjust Pattern to Sensor Failure | .0447 | -.5791 | .1632 |
| Extend Sensor Pattern | .1172 | -.5526 | -.5211 |
| Anticpate Target Movement | -.2909 | .7820 | -.2064 |
| Construct Sensor Monitoring Pattern | .1720 | -.6017 | -.2467 |
| Coordinate Hand-Off | 1.4256 | -.4035 | .6366 |
| Determine Signal Is Valid Contact | -1.3964 | .0029 | .2927 |
| Determine Weapon Setting For Atack | .6826 | .6964 | .0826 |
| Gain Attack Criteria | .4285 | .7912 | -.0787 |
| Determine Target Fix | -.5060 | .7070 | -.1407 |
| Create Sensor pattern | .2664 | -.5176 | -.5525 |
| Manage Equipment and Stores | .0169 | -.4266 | .6182 |
| Classify Signal | -1.3337 | -.0282 | .3539 |
| Compensation for Propagation Conditions | -.2605 | -.6237 | -.3427 |
| Determine Aircraft Launch Position | .6336 | .7694 | -.0585 |

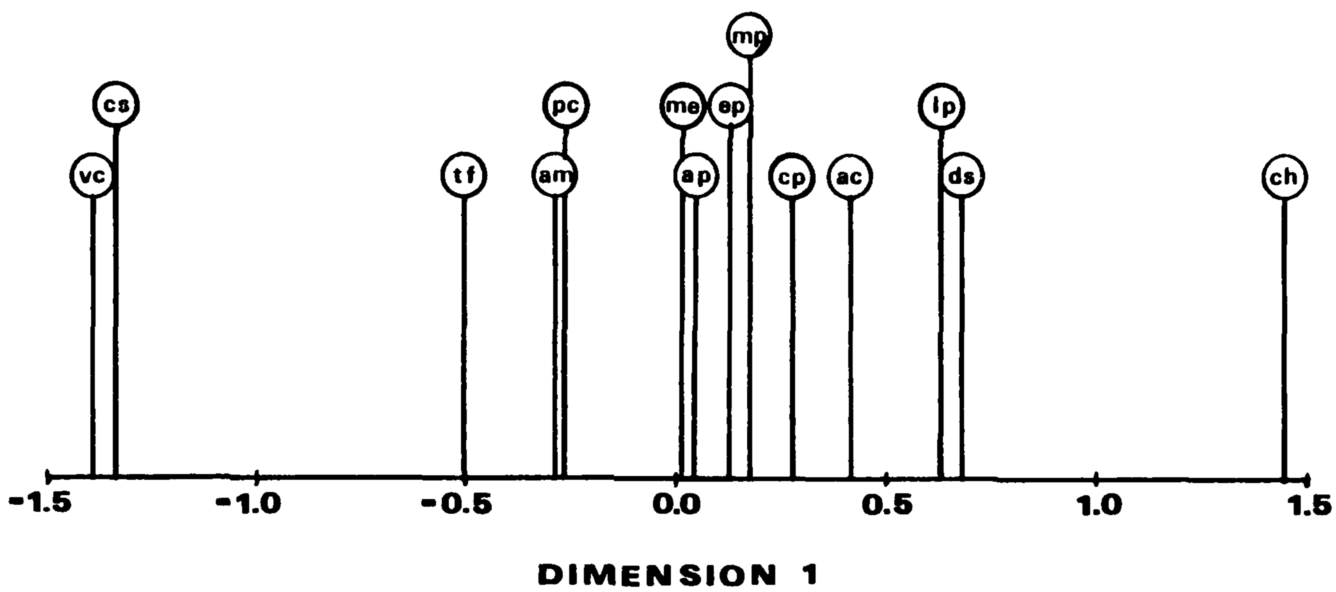


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Figure 8. Dimension 1 Unidimensional Plot

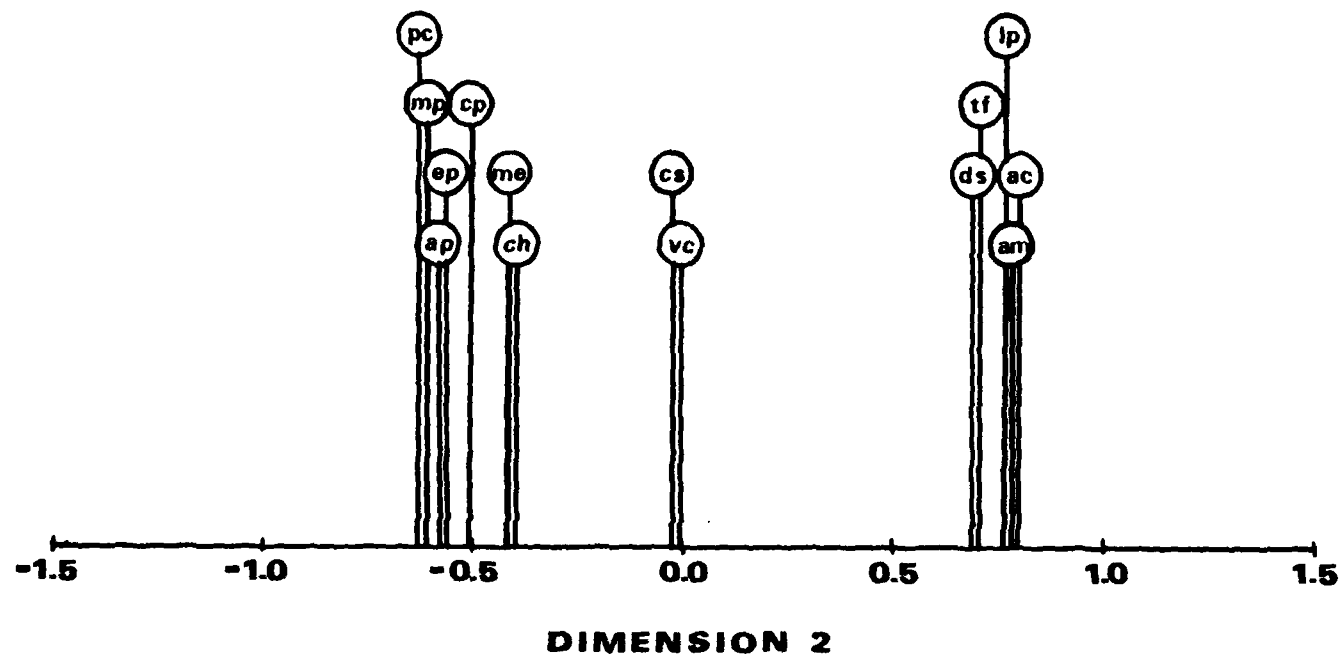


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Figure 9. Dimension 2 Unidimensional Plot

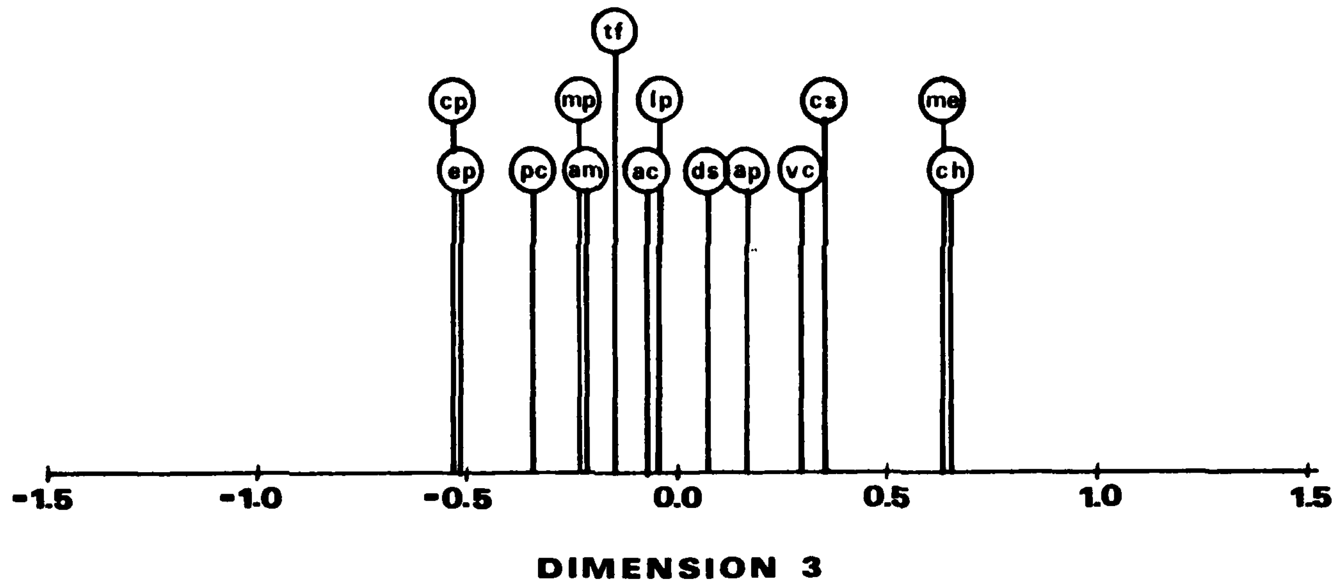


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Figure 10. Dimension 3 Unidimensional Plot

### 1. Interpretation of Dimension One: Workload

This dimension was interpreted as representing the workload of the TACCO (physical and cognitive) when executing the decision function (Figure 8). The extreme points of this mapping - Coordinate Hand-off, Classify Signal, and Determine Signal is Valid Contact lend reinforcement to this interpretation. Although the TACCO is ultimately responsible for the successful completion of the tactical mission, the sensor operators (acoustic and nonacoustic) are required to Classify Signal and Determine Signal is Valid Contact. The TACCO may verify the sensor operator's decision but as far as workload of those decision functions to the TACCO is concerned, the workload is minimal. The workload of these decision functions lie in the interpretation and analysis of target signals, which is more of a sensor operator's function. On the other extreme is perhaps the heaviest workload decision function of the decision set - Coordinate Hand-off. Many inputs are required to be processed and assimiliated to provide a well executed Coordinated Hand-off. Although the format of a Coordinated Hand-off is well established, the degree of detail required to maintain target contact is great.

The implicit ordering of decision functions between these extreme stimuli support the workload interpretation of this dimension. The next three highest decision functions after Coordinated Hand-off - Determine Weapon and Setting, Determine Aircraft Weapon Launch Position, and Gain Attack Criteria - involve great complexity. Because the actual deptn of the target is difficult to assess, the TACCO must use every input to the problem to determine the correct weapon selection and its search setting in order to maximize probability of kill. Maneuvering the aircraft into weapons launch position and gaining attack criteria must occur within a small window in time in order to place a weapon on target. A small miscalculation in the execution of the decision functions could cause the aircraft to be out of position when attack criteria is gained resulting in a lost attack opportunity.

A cluster of five decision functions concerning sensor placement, are found close to the zero point - Create Sensor Pattern, Construct Sensor Monitoring Pattern, Extend Existing Sensor Pattern, Adjust Pattern to Sensor Failure, and Manage Equipment/Stores to Accomodate Present and Future Needs. All of these decision functions exhibit two levels of cognitive workload. The more cognitive level concerns the situational inputs of each function - the decisions that change with time, both present and future. The less cognitive level represents the computer controlled decision inputs such as monitoring sequence, search pattern, and stores remaining, and the formatted procedures established by the On-Scene Commander (such as buoy spacing, type of pattern, and buoy channel numbers).

The three remaining decision functions - Compensate for Acoustic/Atmospheric Propagation Conditions, Anticipate Target Movement, and Determine Target Fix require less work with respect to the TACCO than the 'zero' cluster but more work than the extreme signal processing functions. The computer on board the S-3A has a bathythermal and a radar range program that takes external inputs to establish situational conditions. Anticipating Target Movement can be assisted by the prediciton and ranging computer functions and fixing information is supplied by the sensor operators with confidence levels.

2. Interpretation of Dimension Two: Time Criticality

Dimension two was interpreted as representing the degree of time criticality of the decision functions. The unidimensional representation (see Figure 9) shows three well defined groupings of decision functions, helpful in analyzing this dimension. The most neutral decision functions on the criticality dimension are Deterimine Signal is a Valid Contact, amd Classify Signal. These signal processing functions are considered somewhat time critical in determining the tactics to use against the target but less critical concerning the prosecution of the target.

On the high criticality extreme of the representation, the actual tactical decision functions - Gain Attack Criteria, Anticipated Targert Movement, Determine Aircraft Weapons Launch Position, Determine Target

Fix, and Determine Weapon and Setting for Attack - are closely clustered. The relative differences between the decision functions were very small numerically, suggesting little difference in the degree of criticality. However, the dynamic nature of these decision functions requires expeditious scrutiny of all time critical inputs to reach the most optimal decision.

The remaining decision functions were clustered at the low criticality extreme of the representation. This stimuli subset - Coordinate Hand-off, Manage Equipment/Stores to Accomodate Present and Future Needs, Create Sensor Pattern, Extend Sensor Pattern, Adjust Sensor Pattern to Sensor Failure, Construct Sensor Monitoring Pattern, and Compensate for Acoustic/Atmospheric Propagation Conditions - is very important in the accomplishment of the ASW mission. However, time criticality is not normally a factor in making any of these decisions.

Speed of decision making can be considered synomymous with time criticality for this dimensional interpretation. Figure 9 illustrates areas requiring fast, moderate, and more deliberate decision making.

### 3. Interpretation of Dimension Three: Complexity

Dimension three was interpreted as referring to the degree of complexity in the decision function with respect to the TACCO. Figure 10 shows a rather scattered unidimensional plot of the decision function. Two small clusters on either extreme and an evenly distributed grouping of the remaining decision functions about zero made this dimension the most difficult to interpret.

The decision functions on the high extreme of Complexity - Coordinate Hand-off, and Manage Equipment/Stores to Accomodate Present and Future Needs - showed high degrees of decision complexity, assembling information for hand-off and inventorying sensors. While on the low extreme of the complexity dimension, the stimuli - Extend Sensor Pattern and Create Sensor Pattern - required little original thought and simply followed standard tactics procedures. The complexity of either decision function was minimal.

The remaining decision functions are evenly spaced around zero suggesting moderate complexity. The stimuli - Classify Signal, and Determine Signal is a Valid Contact, - has a greater degree of complexity, processing all inputs to those decision functions. On the other end of the grouping, Compensate for Acoustic/Atmospheric Propagation Conditions, minimizes complexity through computer-assistance programs. The rest of the 'zero' grouping involve implicit degrees of complexity.

## E. PRIORITIZATION OF THE DECISION SPACE

The three dimensions constructed by the MDS analysis of the sorting data represent a geometric model of experienced S-3A TACCOs' understanding of Air ASW decisions. These three dimensions represent the basic implicit relationships that TACCOs used in the Air ASW decision making. Therefore, other relationships or characteristics should exist only as combinations of these underlying features. One such characteristic is priority or importance. Two of the rank orderings, discussed earlier, had as criterion - importance to the mission. This section discusses the implicit combination of these three dimensions used by the TACCOs when they ranked the 14 decision functions using the importance criterion (both with attack and without attack).

The basic technique used to determine TACCO priority functions is termed Priority Mapping, and has been developed directly for this type of application by Zachary [1980b]. It is related to the psychometric techniques known as Preference Mapping [Carrol and Chang 1967] and is based on Coombs [1950] and Bennett and Hayes [1960] notion of Unfolding Analysis.

### 1. Unfolding Analysis and Priority Mapping

In the multidimensional model of the Air ASW decision space, each decision function in the stimulus set has a unique projection or coordinate on each of the dimensional axes. Each dimension is considered to be a scale which measures some relevent perceptual attribute of the decision space. Collectively, the three scales in this model measure all of the independent features needed to represent the perceived interrelationships among decision functions in the decision space. In this model, the three dimensions provide numerical measures of all the important features on which experienced S-3A TACCOs perceive ASW decisions (as shown in Table IX).

Therefore, other salient characteristics of the decision functions must be combinations of the features represented by the axes of the MDS model. These derivative characteristics or features may have differing measurement scales, resulting in different representations within the multidimensional space. The measurement scales include categorical, ordinal, and interval-ratio. The categorical scale partitions the multidimensional space into unordered regions. The ordinal scale provides a graded or ordered partition of the multidimensional space. Finally, the interval-ratio scale represents the feature as a directed vector or curve passing through the multidimensional space.

Unfortunately, little can be done to represent categorical derivative features in the multidimensional model. However, through the use of Unfolding Analysis, it is possible to construct a representation of ordinal or interval-ratio derivative features. The technique is based on the concept that the general form of the representation of a derivative feature in a predefined multidimensional space can be determined by comparing different models of increasing complexity [Zachary 1980b].

Unfolding Analysis restricts itself to four specific formulae which have simple mathematical forms and direct psychological interpretations. Although the analysis could be performed on either ordinal or interval-ratio scale features, the analysis used in this discussion was limited to ordinal scales, consistent with the (ordinal) ranking data.

In Unfolding Analysis, the four models are considered and compared in terms of their ability to represent a given ordinal scale in a multidimensional space. Usually, the ordinal scale is a ranking of a stimulus set by individuals according to some criterion and the multidimensional space is a result of some MDS analysis. Unfolding Analysis attempts to represent the ranking criteria as a function of the MDS dimensionalization.

Techniques, similar to regression, can be used to define an equation which models the criterion representation as a function of the MDS dimensions. Carroll and Chang [1977] developed a set of computational procedures for performing these regression-like analysis. In this analysis, their computational approach is used to model data on perceived priority of decision functions. This adaptation of the model is appropriately termed 'Priority Mapping', since it constructs a mathematical 'map' of the TACCOs intuitive prioritization of the decision functions.

### 2. Four Models of Priority

The Unfolding Analysis and Priority Mapping procedures employ four models of priority. These models are based on a heirarchial structure such that each model is a special case of the next 'higher' model. Each model in the heirarchy subsumes all subordinate models. The models will be explained in terms of ordinal representations consistent with the data set.

An ordinal scale in a multidimensional space divides the space into graded regions, such that a point in one region has a different rank than a point in another region, but the same rank as another point in the same region. In other words, the space is broken into isopriority regions separated by isopriority contours. A geometric representation of the four models showing the isopriority contour structure is shown in Figure 11. For simplicity, Figure 11 and the following discussion are expressed in terms of a two-dimensional space. A generalization of this approach can be extended to three or more dimensions.

The first model (and lowest in the heirarchy) is the vector model. This model assumes that each dimension contributes in a linear fashion resulting in a prioritization defined by stimuli projections onto a vector

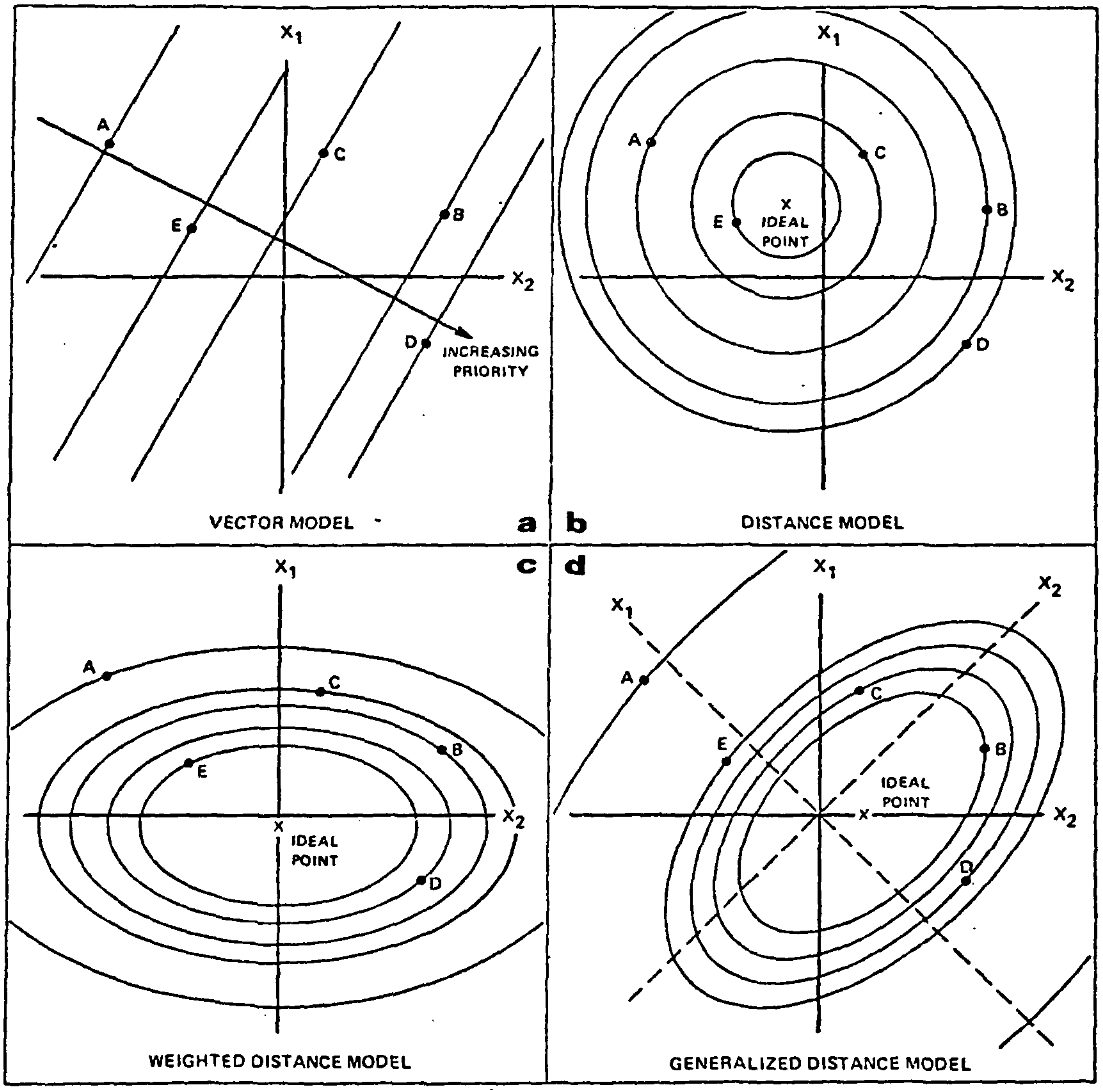



Figure 11. Four Models of Priority

in the multidimensional space. The isopriority contours are lines (in this case) perpendicular to the stimulus vector (shown in Figure 11a). The vector model is similiar to the concept of Multiattribute Utility (MAU). Each dimension (attribute) contributes to the model in a linear way with the relative contribution of each dimension defined by a coefficient assigned to it. The vector model can be compared to the economic's 'more is better' model, because it assumes that whatever the dimension, more of it will contribute to a higher priority.

The remaining three models define priority in terms of distance in the multidimensional space. These models are based on the assumption that there is an ideal point somewhere in the modeled space, such that the closer a stimulus is to the ideal point, the higher the priority of that stimulus. The simplest of the distance models is termed the Unweighted Distance Model or just Distance model. This model prioritizes stimuli strictly according to their distances from the ideal point. This distance measurement for this model is Euclidean in nature yeilding isopriority contours represented by concentric circles around the ideal point (as shown in Figure 11b). The unweighted model assumes each dimension has an equal contribution to priority.

A more general representation in terms of distance allows the distance between the ideal point and each decision to be a function of weighted dimensionality. More specifically, dimensions may not contribute equally to the model so each dimensional axes is given a relative weight. This model, termed the Weighted Distance Model, allows the isopriority contours to assume the general slope of an ellipse parrallel to the dimensional axes as shown in Figure 11c.

In the models previously discussed, an assumption is that each dimension contributes independently to priority. However, interaction may occur among some or all dimensions in constituting the concept of priority. To allow such interactions among dimensions, a model can be constructed by permitting the axes to be rotated before the distances are computed. This model, termed the Generalized Distance Model, allows each dimension to contribute independently and collectively to the priority of an decision function. The isopriority contours are similar to the weighted distance model except the contours can assume any orientation in the space as shown in Figure 11d.

These four models - the vector model, the distance model, the weighted model, and the generalized model - are the mathematical basis for the Unfolding Analysis and Priority Mapping. In Unfolding Analysis, the ability of each model to replicate the ordering of the decisions by the TACCOs, is evaluated and the most applicable model is selected. In Priority Mapping, the specific coefficients of the selected model are determined and a precise mathematical prepresentation of priority is constructed.

## F. UNFOLDING ANALYSIS AND PRIORITY MAPPING OF DECISION FUNCTIONS

Unfolding Analysis procedures were conducted for the two sets of ranking of decision functions by importance. The first analysis considered the rankings by importance in the ASW mission where the goal was an attack on the submarine. The individual rankings are in Appendix D, and the average rankings are given in Table V. The second analysis considered the rankings by importance to the ASW mission where the goal was surveillance of the submarine. The average rankings for this criterion is given in Table VI and the individual rankings are in Appendix D. The priority mapping was conducted with the PREFMAP program developed by Carrol and Chang [1967, 1977], which performs the Unfolding Analysis as described in the last section. PREFMAP, like MINASSA, is a part of the MDSX package of Multidimensional Scaling programs [Coxon et al 1977] available on the Wharton School's DEC-10 Computer. PREFMAP performs Unfolding Analysis by conducting seperate analysis of each individual ranking against the multidimensional configuration of the stimulus set provided by the user.

### 1. Prioritization of Decision Function by Importance in Mission with Attack

Using the PREFMAP program, the analysis began by constructing trial representations of the rankings criterion using each of the four models discussed earlier. These representations produced different rankings of the decisions functions, which can be compared to the actual TACCO rankings to determine the appropriateness of each model. The simplest, most reasonable measure of comparison is the correlation between the actual rankings and the rankings produced by the model. The correlation, when squared, becomes the coefficient of variation, $r^2$, indicating the proportion of variation in the TACCO rankings accounted for in the PREFMAP rankings. A F test statistic can be computed from $r^2$ and used to test the null hypothesis, $H_o$, that the value of $r^2$ is strictly a random result. The values of $r^2$, the F ratio, and the levels of significance are given in Table X.

Table X. Significance of Results for Mission with Attack

| MODEL | $r^2$ | F STATISTIC | REJECTION LEVEL |
|---|---|---|---|
| GENERALIZED | .996 | 116.8 | <.01 |
| WEIGHT DIST. | .982 | 62.6 | <.01 |
| UNWEIGHTED | .943 | 37.4 | <.01 |
| DISTANCE VECTOR | .939 | 51.2 | <.01 |

All four models produced a significant (non-chance) representation of the TACCO data. The next phase of the analysis is to determine which is the best representation.

The most widely used criterion for selecting among models is the goodness of fit measurement between the model and the data. The goodness of fit is measured in all four models by $r^2$ - the coefficient of variation. The $r^2$ value for all four models is greater than .99, indicating a good fit by all models. In fact, each model in the heirarchy accounts for more variation than the lower models. This reinforcing result is an artifact of the PREFMAP algorithm since each heirarchial model increases the complexity of the equation with increases in the number of parameters. Consequently, the model with more parameters will explain more of the variance than the subordinate models. Therefore, it is reasonable to assume that $r^2$ will increase as the heirarchy is traversed from the vector to the generalized model. The fundamental question is whether or not the increase in $r^2$, as the model heirarchy is traversed, is significant as the number of model parameters increase.

To answer this question, a statistical comparison among the model rankings was used. A F statistic was computed from the $r^2$ values of each pair of models (the between-model coefficient of variation) to test the null hypothesis that the increase in the value of $r^2$ as the model heirarchy is traversed is only a chance result. A failure of this hypothsis for a given pair of models indicated that there was not a significant difference in the explanatory power of the two models and the subordinate model would be preferred because it is less complex. The comparison among the four models is shown in Table XI.

Table XI. Comparison of Coefficients of Variation for Mission with Attack

(Each cell: F STAT / SIGN.)

| MODEL | GENERALIZED | WEIGHTED | UNWEIGHTED |
|---|---|---|---|
| WEIGHTED | 5.1<br>.022 | | |
| UNWEIGHTED | 11.2<br>.018 | 7.4<br>.019 | |
| VECTOR | 10.1<br>.021 | 5.5<br>.030 | 21.0<br>.424 |

As illustrated in Table XI, the generalized distance model is significantly more powerful than the other models with a confidence of greater than 95 percent. Therefore, the generalized distance model was selected to represent the TACCO rankings according to this criterion.

Having selected the 'best' model for representing the ranking criterion, a precise priority function was derived using the PREFMAP program. The importance of priority of a decision function j in a mission with attack ($P_{wa}(d_j)$) was given by:

$$P_{wa}(d_j) = -.148x^2_{j1} - 1.74x^2_{j2} - .417x^2_{j3} + .330x_{j1}x_{j2} + .774x_{j1}x_{j3} - 1.20x_{j2}x_{j3} + .018x_{j1} - .091x_{j2} - .670x_{j3} + .727$$

where $x_{j1}$ is the coordinate of $d_j$ on dimension 1

$x_{j2}$ is the coordinate of $d_j$ on dimension 2 and

$x_{j3}$ is the coordinate of $d_j$ on dimension 3.

The values of $x_{j1}$, $x_{j2}$, $x_{j3}$ are given in Table IX.

The priority values of the fourteen decision function generated by this function are given in Table XII.

Table XII. Decision Function Prioritization for Mission with Attack

| PRIORITY RANK | NAME | PRIORITY SCORE |
|---|---|---|
| 1 | GAIN ATTACK CRITERIA (AC) | -.2489 |
| 2 | CLASSIFY SIGNAL (CS) | -.2464 |
| 3 | DETERMINE SIGNAL IS VALID CONTACT (VC) | -.1947 |
| 4 | DETERMINE AIRCRAFT WEAPON LAUNCH POSITION (LP) | -.1852 |
| 5 | DETERMINE WEAPON AND SETTING FOR ATTACK (DS) | -.1785 |
| 6 | ANTICIPATE TARGET MOVEMENT (TM) | -.1431 |
| 7 | DETERMINE TARGET FIX (TF) | -.1198 |
| 8 | CREATE SENSOR PATTERN (CP) | .0402 |
| 9 | CREATE SENSORING MONITORING PATTERN (MP) | .0444 |
| 10 | EXTEND SENSOR PATTERN (EP) | .0673 |
| 11 | COMPENSATE FOR PROPAGNATION CONDITIONS (PC) | .1368 |
| 12 | ADJUST PATTERN TO SENSOR FAILURE (AP) | .1867 |
| 13 | MANAGE EQUIPMENT AND STORES (ME) | .1980 |
| 14 | COORDINATE HAND-OFF (CH) | .3656 |

These values represent the relative priority of the decision functions in a mission with attack. The lower values (i.e., negative) in Table XII indicate a higher priority and the higher values represent a lower priority. This ordering is the result of the TACCOs assigning lower ranks to the more important decisions and higher ranks to the less important decisions (PREFMAP program merely maintains this directionality in its computations).

## 2. Prioritization of Decision Function by Importance in Mission Without Attack

An identical analysis was conducted for the TACCO rankings of decision functions where the criterion was importance to ASW mission without attack. PREFMAP constructed the initial representations to determine which of the four models produced 'best' representation of the TACCO data. The coefficient of variation ($r^2$) and the statistical test (F) (Table XIII) were used to determine which model is the best representation.

Table XIII. Significance of Result for Mission Without Attack

| MODEL | $r^2$ | F STATISTIC | REJECTION LEVEL |
|---|---|---|---|
| GENERALIZED | .997 | 130.9 | <.01 |
| WEIGHT DIST. | .949 | 21.8 | <.01 |
| UNWEIGHTED DISTANCE | .881 | 16.7 | <.01 |
| VECTOR | .795 | 13.0 | <.01 |

As with the previous criterion, the null hypothesis can be rejected for all four models, indicating that a significant representation of the TACCO ranks were provided by all models.

As before, the four models were compared against each other to determine the model of best representation. The 'between model' F statistic was used, testing the null hypothesis, $H_o$, that the increase in the proportion of variance accounted for by the more powerful model was a chance result accounted for by its increased number of parameters. Table XIV show the 'between-model' F statistic and the associated significance level.

Table XIV. Comparison of Coefficients of Variation for Mission Without Attack

| MODEL | GENERALIZED | WEIGHTED | UNWEIGHTED |
|---|---|---|---|
| | F STAT<br>SIGN. | | |
| WEIGHTED | 18.7<br>.008 | | |
| UNWEIGHTED | 27.3<br>.003 | 4.7<br>.051 | |
| VECTOR | 39.6<br>.002 | 7.0<br>.016 | 6.5<br>.031 |

There were more pronounced differences in the significance levels between models in Table XIV than in Table XI. More specifically, the Generalized Distance Model was found to be significantly better in representing the TACCO data with a confidence of greater than 99 percent. As a result, the Generalized Distance Model was selected as the most appropriate model for the no attack criterion.

As in the previous analysis, the PREFMAP program was used to 'map' the precise mathematical priority function. Using this algorithm, the importance of decision j on a mission without attack ($P_{woa}(d_j)$) was given by:

$$P_{woa}(d_j) = -.230x^2_{j1} -1.93x^2_{j2} -.815x^2_{j3} +.623x_{j1}x_{j2} +.385x_{j1}x_{j3} -.592x_{j2}x_{j3} +.226x_{j1} +.260x_{j2} -.410x_{j3} +.888$$

where $x_{j1}$ is the coordinate of decision j on dimension 1

$x_{j2}$ is the coordinate of decision j on dimension 2 and

$x_{j3}$ is the coordinate of decision j on dimension 3.

The values of the $x_{ji}$, as before, were given in Table IX. The priority values for the fourteen decision functions are given in Table XV.

Table XV. Decision Function Prioritization for Mission Without Attack

| PRIORITY RANK | NAME | PRIORITY SCORE |
|---|---|---|
| 1 | CLASSIFY SIGNAL (CS) | -.2309 |
| 2 | DETERMINE SIGNAL IS VALID CONTACT (VC) | -.2210 |
| 3 | DETERMINE TARGET FIX (TF) | -.1612 |
| 4 | ANTICIPATE TARGET MOVEMENT | -.1473 |
| 5 | COORDINATE HAND-OFF (CH) | -.1246 |
| 6 | EXTEND SENSOR PATTERN (EP) | -.0637 |
| 7 | CREATE SENSOR PATTERN (CP) | -.0539 |
| 8 | CONSTRUCT SENSOR MONITORING PATTERN (MP) | -.0523 |
| 9 | COMPENSATE FOR PROPAGATION CONDITIONS (PC) | -.0456 |
| 10 | MANAGE EQUIPMENT AND STORES (ME) | .0203 |
| 11 | ADJUST PATTERN TO SENSOR FAILURE (AP) | .0539 |
| 12 | GAIN ATTACK CRITERION (AC) | .2025 |
| 13 | DETERMINE AIRCRAFT WEAPON LAUNCH POSITION (LP) | .3563 |
| 14 | DETERMINE WEAPON AND SETTING FOR ATTACK (DS) | .4245 |

These values represent the prioritization of the decirsion functions in the ASW mission without attack on the submarine. For reasons discussed in the previous section, the smaller values represent higher priority in Table XV.

# V. DISCUSSION

## A. RESULTS

### 1. Summary

In this thesis. a methodology was developed that prioritized ASW decision functions according to different criteria. However, to more fully understand the results of the methodology and its components, the purpose of this thesis should be reviewed. The objective of this effort was to examine ASW decision making in the S-3A through the use of mathematical modeling techniques and to establish a prioritization technique for the development of decision aids to assist decision making in the system. An examination of the S-3A ASW decision making included discussions of the history of ASW, the four and six partition spacing of the Air ASW mission, and finally the fourteen decision function partition of the Air ASW decision space. S-3A TACCOS sorted and ranked the 14 decision functions through the use of the mathematical modeling techniques of Multidimensional Scaling and Unfolding Analysis, a priority mapping of the fourteen decision functions was produced.

The Multidimensional Scaling representation of the decision functions was determined to have three orthogonal dimensions or axes through a goodness of fit test. The dimensions were interpreted as follows:

Dimension One - Workload

Dimension Two - Time Criticality

Dimension Three - Complexity

It should be noted that this interpretation of dimensional meaning is not unique. The interpretations, to a great degree, are subjective in nature relying upon the analyst's understanding of the interrelationships of the stimulus set. However, the relative positions of the stimuli on each dimension (Figures 8 through 10) is unique so the interpretations of the dimensions should be roughly equivalent from analyst to analyst.

The Unfolding Analysis determined that the importance rankings were best represented by the Generalized Distance Model in terms of priority functions. Only two of these four rankings were utilized in the unfolding analysis. The criterion of importance was assumed to be the most important feature of the priority mapping, so the criteria of importance to the ASW mission with attack and importance to the ASW mission without attack were selected and the criteria of urgency and workload rankings were used to validate the resulting Priority Mapping algorithm.

Finally, the results of the Multidimensional Scaling program (MINASSA) and the Unfolding Analysis program (PREFMAP) were used to 'map' the precise priority function. From the two priority functions, a prioritization of the ASW decision space was established according to both criteria (see Tables XIII and XV).

As a result, a priortization technique for Air ASW decision functions was established for the development of decision aids in the S-3A. The fundamental question raised by the priority ranking shown in Tables XIII and XV is what is the meaning of this prioritization of decision functions.

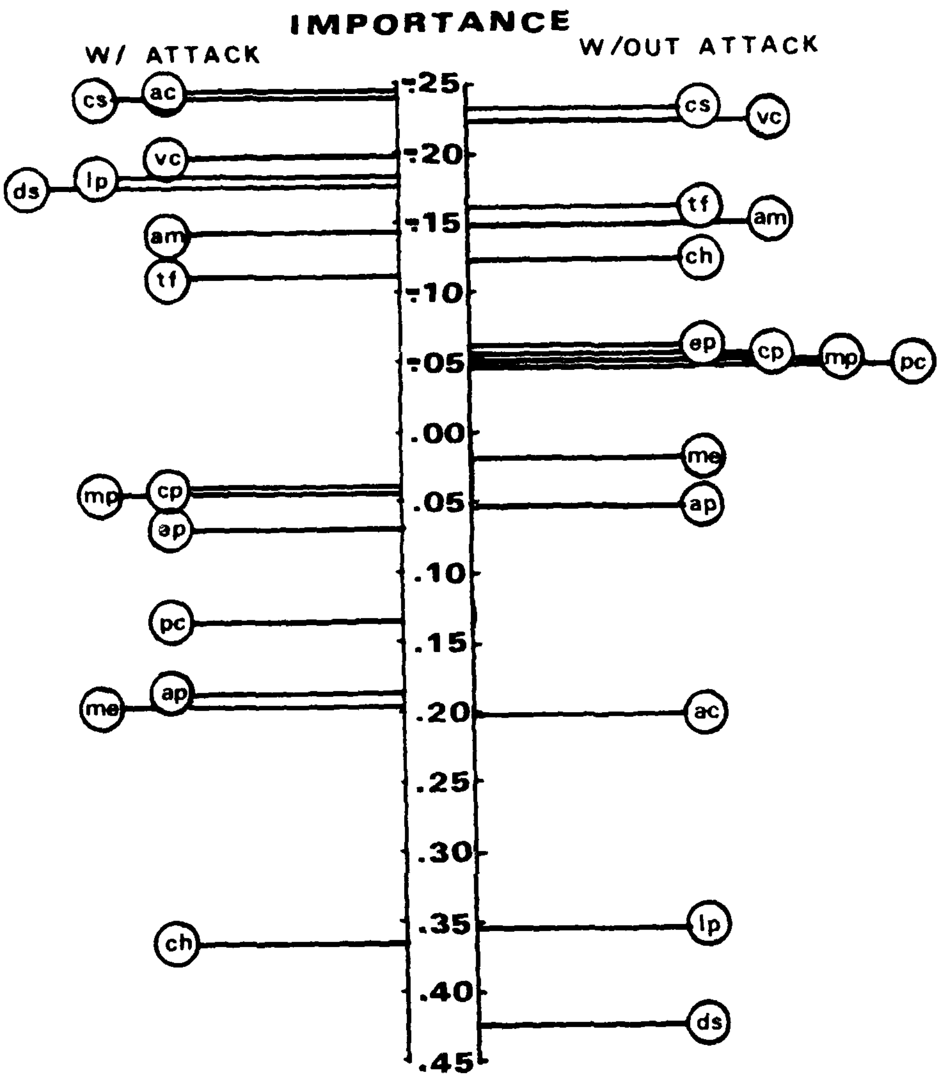
2. Interpretation of Results

To better interpret the results of the priority mapping function, a relative plot of the 14 decision functions is given in Figure 12 for the attack and no-attack criterion. The relative position of the decision functions on this priority scale for each criterion yields an implicit ordering of areas in which TACCOs think decision aids would be useful.

a. Gain Attack Criteria

The Gain Attack Criteria decision function was ranked first in the priority scale for the 'attack' criterion. Intuitively, this result is not surprising in a mission where the goal is attacking the submarine. The TACCOs interviewed felt that in a mission where attack on a hostile threat was the goal, if attack criteria was not gained, the mission would be a failure.

The implication, from the priority scale of the importance to the ASW mission with attack, is that more energy should be channeled into the area of decision aids




KEY
AP - ADJUST PATTERN TO SENSOR FAILURE
EP - EXTEND SENSOR PATTERN
AM - ANTICIPATE TARGET MOVEMENT
MP - CONSTRUCT SENSOR MONITORING PATTERN
CH - COORDINATE HAND-OFF
VC - DETERMINE SIGNAL IS VALID CONTACT
DS - DETERMINE WEAPON AND SETTING FOR ATTACK
AC - GAIN ATTACK CRITERIA
TF - DETERMINE TARGET FIX
CP - CREATE SENSOR PATTERN
ME - MANAGE EQUIPMENT/STORES
CS - CLASSIFY SIGNAL
PC - COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS
LP - DETERMINE AIRCRAFT WEAPON LAUNCH POISITON

Figure 12. Priority Score of Decision Functions (S-3A)

concerned with assisting the TACCO in determining when attack criteria has been reached. Additionally, Gain Attack Criteria ranked highest in the average rankings for importance to ASW mission with attack (Table V) and Workload (Table VIII) and second highest in the ranking for the Uregency (Table VII). This placement distinguishes this decision function as time-critical for the TACCO.

Placement of the Gain Attack Criteria decision function in the MDS solution space (Figures 5 through 10) also confirms this distinction. Although this decision function is positioned near the middle of dimension three (Complexity), it is located at the positive extreme of both dimension one (Workload) and two (Time Criticality). This positioning indicates a highly time critical and work intensive decision function. Based upon this analysis, the decision function - Gain Attack Criteria - represents an area in the Air ASW mission where implementation of a decision aid would be of great benefit.

b. Classify Signal and Determine Signal is Valid Contact

The decision functions - Classify Signal and Determine Signal is Valid Contact - were ranked first and second in the priority scale for the 'no attack' criterion (Figure 12) and ranked second and third on the priority scale for the 'attack' criterion (behind Gain Attack Criteria). This position on the high extreme of both priority scales was unexpected however it was clear that the

TACCOs felt these two decision functions to be the heart of a successful ASW mission. The TACCOs felt that the entire mission was dependent on the proper evaluation of an incoming signal (that could be a hostile threat) and suggested that because this evaluation is so important, there is little room for error regarding either decision function.

The placement of these two decision functions (Classify Signal and Determine Signal is Valid Contact) on the high extreme of both priority scales suggest that these two areas in the Air ASW mission are most important in the accomplishment of the mission. The implication is that decision aids should be developed for both decision functions. Furthermore, both decision functions were ranked high in the average rankings for importance to mission with attack and without attack. In the average ranking for Urgency, both decision functions were positioned in the center of the ranking, indicating that Classify Signal and Determine Signal is Valid Contact are not critical in terms of Urgency. The placement of the decision functions at the bottom of the average ranking for Workload indicates that both decision functions do not add to the TACCO Workload. In the S-3A, Classify Signal and Determine Signal is Valid Contact are responsibilities of the TACCO but these decision functions are normally delegated to the sensor operators with inputs to the TACCO.

The two decision functions - Classify Signal and Determine Signal is Valid contact - in the sample of the fourteen lay at opposite extremes in two dimensions and in the center of the third of the MDS space (Figures 5 through 10). In dimension one, Workload, Classify Signal and Determine Signal is Valid Contact lies at the very negative extreme representing light workload (Figure 8).

On the second dimension, Time Criticality, the two decision functions are clustered at the 'zero' point, well away from the other two well-defined groupings (Figure 9). This result suggest that Classify Signal and Determine Signal is Valid Contact are not as time critical as the 'attack' functions because the confidence in the Contact Validity normally improves over time. However, both decision functions are more time critical than the 'tactics' functions because confidence improves only after contact is established.

The third dimension, complexity, located both decision functions in the positive region indicating a high degree of complexity (Figure 10). Many inputs into the classification or verification decisions from all sensors suggest that the degree of complexity increases with the number of sensors employed. Classify Signal and Determine Signal is Valid is a sine quad non.

The remaining eleven decision functions were not addressed further because the apparent order of the three discussed decision functions is not implicitly present in the ordering of the last eleven functions. This problem will be discussed further in the Conclusion and Recommendations sections.

3. Comparision of Results to Similiar Work

This analysis has established priority scales for both attack and no attack decision situations. The fourteen decision functions were ordered in importance by the use of Multidimensional Scaling combined with Unfolding Analysis.

Zachary (1980 a and b) used the same prioritization methodology used in this analysis in conjunction with P-3C TACCO inputs. the results of his analysis was very similar to this analytical result. Although the P-3C is a shore based ASW aircraft with a crew of 11, the function of the TACCO is very much like that of the S-3A TACCO. Consequently, similiar results in the prioritization analysis would not be surprising.

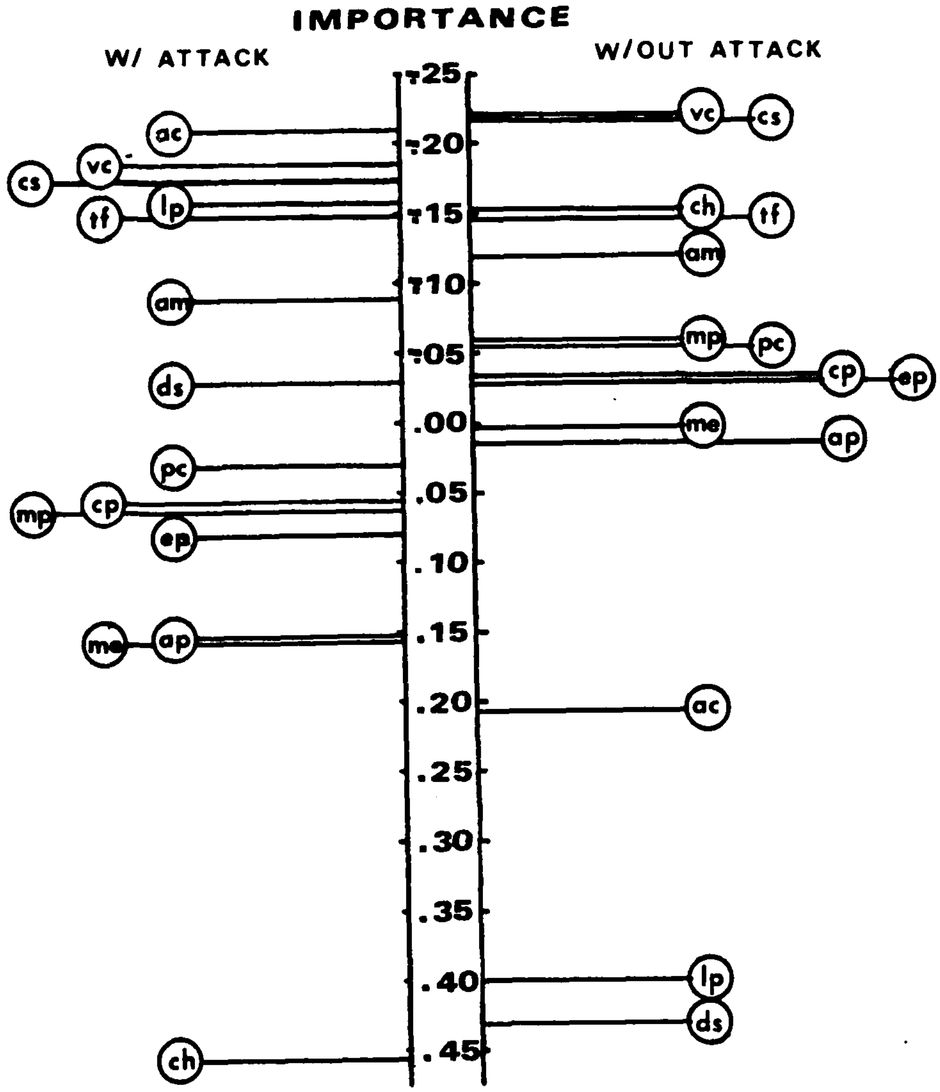
Zachary's prioritization for Importance to the ASW Mission with Attack on the Submarine was very nearly the same as the S-3A prioritization. These were minor inversions of one or two decision functions in the final priority scale comparisions, however the differences in the aircraft system capabilities suggest that this result is reasonable. The comparision of decision function prioritization for mission without attack on submarine provided a similiar result. The priority scales were very similiar except for the inversion of one or two decision functions due to aircraft and tactical dissimiliarities. Figure 13 shows Zachary's priority scale for both attack and no-attack for the P-3C. These priority scales are presented in the same format as Figure 12 for ease of comparison.

Zachary's analysis also used three dimensions as representative of the MDS decision space (discussed in Chapter Four). Zachary's interpretation of his three dimensions for the P-3C data was similiar to this analysis, however, the placement of each decision function in the decision space was markedly different. His dimensional plots can be found in Appendix E. This difference could be contributed to sampling differences, aircraft differences, or training differences between S-3A and P-3C TACCOs.

Zachary's results reinforces the applicability of the results of this analysis. Although two analyses of similiar data do not necessarily validate a new methodology, the degree of agreement between results suggest further application could be of great benefit in the area of ASW.

## B. CONCLUSION

This thesis has established that a workable mathematical technique exist for the prioritization of Air ASW decision




KEY

AP - ADJUST PATTERN TO SENSOR FAILURE
EP - EXTEND SENSOR PATTERN
AM - ANTICIPATE TARGET MOVEMENT
MP - CONSTRUCT SENSOR MONITORING PATTERN
CH - COORDINATE HAND-OFF
VC - DETERMINE SIGNAL IS VALID CONTACT
DS - DETERMINE WEAPON AND SETTING FOR ATTACK
AC - GAIN ATTACK CRITERIA
TF - DETERMINE TARGET FIX
CP - CREATE SENSOR PATTERN
ME - MANAGE EQUIPMENT/STORES
CS - CLASSIFY SIGNAL
PC - COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS
LP - DETERMINE AIRCRAFT WEAPON LAUNCH POISITON

Figure 13. Priority Score of Decision Functions (P-3C)

functions, specifically and a general application could be established for any complex decision space. The prioritization methodology developed in this thesis represents a new approach to the problem of assigning priorities to decision stimuli. This methodology is based on two assumptions:

1) the decision space is a multidimensional domain where all underlying dimensions have some potential relevancy to the final prioritization.

2) inputs to the decision space must be based on experience, judgement and intuition.

The prioritization methodology, Priority Mapping, produced two siginificant results. First, the MDS portion of the methodology identified the three dimensions which underlie the TACCO decisions. Secondly, the 'marriage' of the MDS results and the Unfolding Analysis provided a numerical prioritization of the Air ASW decision space.

The Priority Mapping algorithm has several interesting characteristics. First, the sorting and ranking positions of the data collection is only required once. Repeated testing or interviewing of the same subjects is not necessary as in many consensus techniques such as Delphi. Ease of data collection is a definite advantage of this technique. Second, specific as well as general questions can be answered by reweighting the parameters of the MDS portion of the algorithm (as discussed in Chapter IV). Third, an advantage of this algorithm is the built-in cross checks and validations carried out by the interaction of the average rankings, MDS unidemnsional plots, and the priority scales. In other words, placement of a particular stimulus on the priority scale should be reflected in that stimulus' placement on the MDS plots and in the average rankings of the test criterion. Additionally, the priority scale and average ranking place would have a positive influence on the analyst's interpretation of the MDS dimensions. Fourth, the Priority Mapping algorithm provides more information about the stimulus set than a ranking or an MDS dimensional analysis alone. To achieve similar results using only ranking task or sorting task, the subjects would have to agree completely on the placement of each stimuli. The algorithm eliminates the need for concensus by combining the two techniques into a predictor model.

The operational application of the priority mapping algorithm to fleet assets is where the developmental 'pay-off' is received. This technique has advantages that unit commanders can appreciate:

1) ease of data collection - simple forms with simple instructions. Any sailor could administer the interview with favorable results.

2) speed of data collection - fast with little confusion. The unconstructed sorting and rankings for a large stimulus set would take less time than

other similiar techniques (i.e. Pairwise MDS) with much smaller stimulus sets.

3) revisit requirements - one data collection visit to operationsl units. The unit commander is not compelled to provide subjects for data collection or verification time after time.

4) tangible results - a priority scale of the stimulus set. A priority scale of the stimulus set is tangible results of the data collection, providing real answers to operational problems.

Many of the techniques discussed in Chapter II do not exhibit these advantages. Fleet acceptance of problem solving methodologies is essential to the development of new software and hardware to meet any present or future threat.

This prioritization methodology shown in Figure 3 can be adjusted to fit any complex decision space provided the assumptions of dimensional relevency and judgmental inputs are not violated. The methodology is flexible enough to be used by any branch of the Armed Forces or any sector of industry. Areas of time critical, work intensive, multi-faceted decision situations are ideal targets for the implementation of the prioritization methodology. The implementation of this technique will identify decision situations where decision aids would be most beneficial.

## C. RECOMMENDATIONS

The decision functions - Classify Signal and Determine Signal is Valid Contact - are at the top of the priority scale of the 14 decision functions defining the Air ASW decision space for the S-3A. Both decision functions were the highest priority in the no-attack mission and second and third highest priority in the attack mission. Therfore, it is recommended that a decision aid be developed to assist the S-3A TACCO in the execution of the decision funcitons - Classify Signal and Determine Signal is Valid Contact.

Although the ASW decision space has been prioritized for the S-3A, the explicit priority ordering of Classify Signal and Determine Signal is Valid Contact across both priority scales is not readily apparent in the remaining decision function. In other words, it is difficult to assess which of the remaining 12 members of the S-3A ASW decision space would be next in priority across both priority scales. However, an algorithm for combining the relative weights of each priority scale across all decision functions such as the Mission Operability Assessment Technique [Helm and Donnell, 1978] would solve the problem by providing one priority scale across all criterion.

Therefore, it is recommended that an algorithm be developed that would combine priority scalings over all relevant criterion to achieve a combinational prioritization of the decision space that would be more useful in the development of decision aids.

## APPENDIX A

### TEXT OF INTRODUCTORY BRIEFING GIVEN TO S-3A TACCOS PRIOR TO MULTIDIMENSIONAL SCALING INTERVIEWS

I would like to begin by thanking you all for coming here today to help us in this effort. You've been asked to come here because of your familiarity with ASW and ASW decision making. Before we ask you some specific questions about ASW, I'd like to begin by providing a brief background on what it is that we mean by decision aids and decision aiding, what the overall structure of our program is, where we have been, and why we have come here to talk to you. As good a place as any to begin is with the definition of a decision aid.

Very simply put, a decision aid is any kind of device that helps humans make better, more efficient, clearer, and faster decisions. Now, obviously, a wide range of possible things can be considered decision aids - from a pencil and a sheet of paper which enable you to do calculations to large computer systems and programs. What we're most interested in are specific tools that will enable you as a TACCO to interact with your on-board computer system to help you the kinds of decisions that you have to make in the course of an ASW mission.

The Navy's interest in decision aiding has been increasing significantly recently because of the realization that warfare, in general, and ASW, in particular, is becoming more automated and more highly technological. The speed and complexity with which decisions must be made is increasing constantly to a point where, in the not too distant future, you as TACCOs, will be overloaded, possibly beyond your capability to make necessary decisions within a reasonable amount of time. Therefore, the Navy is interested in developing computerized systems of decision aids that will help you keep pace with the increasing automation on-board your aircraft. It should be pointed out that these decision aids will not take you out of the decision making process or automate your functions. Rather, they will provide you with better, more intelligent support from machines and will give you time to do what you do best - think and make decision. The whole concept of decision aiding is based on the notion that the most complex, useful, and important piece of equipment on any platform is the human-brain. Humans are on-board to make decisions; but computers and other kinds of devices can assist by managing information, making certain kinds of data available at your fingertips, helping you remember things (like the procedures you must go through to accomplish a specific function), performing certain kinds of calculations for you, and so forth.

Decision aids can work at a variety of levels. Simple

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decision aids can, for example, provide very rudimentary bookkeeping functions or provide checklists of things that must be done. More complex decision aids can "ask" you the questions that you should be asking yourself. Still more complex decision aids can anticipate some of the information that you may want, based on your past performance; they can perform certain kinds of calculations automatically so that the results of the calculations will be available when requested; they can make certain kinds of inferences about what might happen in the future enabling you to play "what if" games to find out what results might be obtained if a specific course of action is undertaken. These latter things, which are at the higher end of the spectrum of the capabilities of decision aids, are the ones that we're most interested in.

To give you a feeling for the types of aids that are possible, I'd like to review some of the other decision aid projects of this type that are on going today in the Navy. The largest decision aiding effort to date has been undertaken by the Office of Naval Research (ONR). Their program has concentrated on developing a variety of decision aids for carrier-based air strike operations. Some of the specific problems to be addressed by these decision aids are; planning the ingress route for an incoming carrier-based air strike or reconnaissance mission through a complex sensor field; determining the specific timing of alpha type air strikes; task force EMCOM planning; and overall air strike campaign planning. The decision aids being developed by ONR are very high level decision aids, both in the sense that they provide a great deal of assistance to the human and in the sense that they deal with very high level command and control decisions (at the task force commander level or higher).

More germaine to our discussion today is the effort that we have undertaken under the joint sponsorship of the Naval Air Development Center and the Office of Naval Research to identify possible decision aids for on-platform ASW operations. I'd like to review some of the earlier parts of this effort to clarify why we are here today.

We began our effort by looking at the ASW platforms that will be in use in the 1980-1985 timeframe - the P-3C, the S-3A, and the LAMPS MK-III. We examined the specific missions that are undertaken by these three platforms in order to define a generic or generalized ASW mission, to identify commonalities in the missions flown by the three platforms, and to identify some of the critical difference both in crew functions and in the details of the missions that were undertaken. We then constructed a flowchart of the sequence of operations that takes place in the generalized mission. The mission was subdivided into very broad categories - movement to the search area, on-station search, prosecution of the contract, possibly culminating in attack and destruction of a hostile submarine. These states were then subdivided into the detailed steps that involved specific decision about classification and sensor extension of search area, and anticipation of target movement. We identified the specific sequences in which these decisions were made, recognizing that the interrelations between these decisions are highly dependent on the sequential nature of the ASW mission. The decisions that take place in the attack phase, for example, are dependent upon the succesful completion of those portions of the mission that relate to search and early prosecution of a contact. Ultimately, we identified six broad areas that we termed decision making situations. We defined a decision making situation as a portion of a mission in which complex sequence of decisions has to be made by the TACCO. These situations were complex because they involved trading off a number of factors against one another. The six decision situations were:

1) On-Station Search,
2) Contact Classification/Verification
3) Target Localization,
4) Surveillance Tracking,
5) Lost Contact Reacquisition, and
6) Attack Planning.

The next issue we addressed in our program was the relative priority of each of these situations. By prioritizing the decision situations, we felt that we were immediately confronted by the problem that there was no single dimension, or criteria, by which we could prioritize the decision situations. They obviously are influenced by their sequence in the mission. They are also influenced by varying time constraints on the decisions that must be made in each situation and how busy the TACCO is in each situation. The more we thought about it, the more different criteria for prioritization we were able to define. It became clear to us that one of the problems was that we, as analysts, could not determine the prioritization. We decided that the only way to determine the specific criteria that were relevant to the prioritization of these decisions was to ask the people who made these kinds of decisions, people such as yourselves. That is why we are here today. We want to determine how the various decisions that you, as TACCOs make, should be pritoritized. To do this, we have to determine the dimensions or criteria by which these decisions are interrelated in your minds. Then we have to determine the importance or priority of these decisions in a mission.

There are a number of techniques that can be used to do this. One way would be to ask you, in very lengthy and detailed discussion, to try to identify the dimensions which are salient to ASW decision making for you. But besides taking a lot of your time, it is not clear that the technique would work. People are often very unclear about the underlying principles they use to think about common, everyday things, like decision making. In addition, we would have the problem of resolving the differences we encountered between the various people we talked to. So instead, we have decided to use a more formal mathematical technique known as multidimensional scaling which will take less of your time and will enable us to determine both the dimensions and the relative importance of the various decisions from the same set of data. Multidimensional scaling uses the computer program to calculate the dimensions from very simple judgements made by you about the basic similarity or difference among these various decisions. We also decided that we wanted to address not just the broad analytic catefories that we have called decision situations, but more precise, meaningful, specific decisions that are made by TACCOs. We identified 14 of these decisions, many of which occur in several of the decision situations. There are, of course, many more decisions that are made in the course if a mission but the 14 decisions that we chose were ones that appeared in more than a single decision situation or ones that seemed particulary amenable to decision aiding.

You have in front of you a set of cards.[1] Each card describes one of these decisions. We're going to ask you to make judgements about which decisions you feel are similar or dissimilar, and to rank them by various criteria. The results of these judged similiarities and rankings will be

-----

[1] Card-packs describing the 14 decision functions passed out to interviewees at this point.

used by the multidimensional scaling process to mathematically determine a set of relationships between these decisions that will help us in prioritizing them. It will also help us to understand the kinds of distinctions that you find most relevent among these various decisions. But, most importantly, we feel it will enable us to relate our analysis in a concrete way to your knowledge, experience, and intuition of the ASW missions. With your help, we will be able to determine the best places to apply decision aiding techniques in the ASW mission.

I'd like to add one other note about the way in which you should sort and rank these decision functions in later portions of this procedure. Do not sort or rank the decisions in terms of how you think a decision aid could help you make these decision nor in terms of how you think they could be made better, but rather in terms of how you currently go about making these decisions and how they currently are handled on the platforms on which you have worked.

# APPENDIX B

## RESPONSE FORMS FOR INTERVIEWS

This appendix contains the forms on which the TACCO's interviewed at NAS Cecil Field recorded the results of the unconstrained sorting and four rankings. All of the pages in the appendix were given to each interviewee as a stapled packet. The first page was used to record some general biographical information on the respondent. The next two pages provided the instructions and response sheet for the unconstrained sorting of the ASW decisions. The remaining pages provided the instructions and response forms for four different rankings of the fourteen decisions.

## BIOGRAPHICAL INFORMATION

Aircraft Type: ______________________________

Rank/Designator: ______________________________

Organization: ______________________________

Date TACCO Designation: ______________________________

Date Mission Commander (if applicable): ______________

Deployment Locations as TACCO (and dates): ____________

______________________________________________

______________________________________________

______________________________________________

## INSTRUCTIONS FOR THE 'SORTING" TASK

You have been given a pack of fourteen yellow caards. On each of these cards is a decision or problem that is encountered in an ASW mission. You have all probably faced these problems many times in your experience as TACCOs. Each decision is in some way different from all the others, but each decision is not totally unique; some of the decisions are more alike than others. What we would like you to do is arrange these decisions and problems into groups according to how similar they are. That is, if these are a number of cards which represent decisions or problems you feel that, based on your experience, are similar, then place all these cards together. If there is a card which you think is sufficiently unique that it isn't similar to any of the others, then place it in a group by itself. There is no limit on the number of groups you can make or on the number of cards you can place in each group. While the final definition of what constitutes similar decisions is left to you, we would like you to think of it as referring to decisions or problems which somehow solve in the same way or which place similar demands on you as TACCO.

INSTRUCTIONS: Record each group of decisions you have formed on a separate block below. Take one group and write the code for the decisions in it on the blank line provided. Then do the same for another group in the next block until each group has been recorded in a separate block. If you wish, you may also include a short phrase describing the similarity you saw in that group of decisions.

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GROUP ______________________________
______________________________
______________________________

---

GROUP ______________________________
______________________________
______________________________

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GROUP ______________________________
______________________________
______________________________

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GROUP ______________________________
______________________________
______________________________

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GROUP ______________________________
______________________________
______________________________

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GROUP ______________________________
______________________________
______________________________

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GROUP ______________________________
______________________________
______________________________

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## INSTRUCTIONS FOR RANKING 1

We would like you to rank these decision problems in the order in which a less-than-optimal decision would have the most detrimental effect on the mission. The decision problem for which a less-than-optimal decision would have the least detrimental impact on the mission should be ranked last, and the decision problem for which a less-than-optimal decision would have the greatest detrimental impact on the mission should be ranked first. For the mission, assume that it is an ASW mission in which the submarine is to be attacked and destroyed if possible.

INSTRUCTIONS: Enter the two-letter codes for the decisions below in the order in which you ranked them. That is, write, the code for the decision you ranked first next to '1.', for the decision you ranked second next to '2.' and so on.

1. ________
2. ________
3. ________
4. ________
5. ________
6. ________
7. ________
8. ________
9. ________
10. ________
11. ________
12. ________
13. ________
14. ________

## INSTRUCTIONS FOR RANKING 2

Rank the decisions according to the same criterion as in the previous case, but for the mission, assume as ASW mission in which the submarine is only to be tracked and handed-off to a relief platform.

INSTRUCTIONS: Enter the two-letter codes for the decisions below in the order in which you ranked them. That is, write the code for the decision you ranked first next to '1.', for the decision you ranked second next to '2.' and so on.

1. ________
2. ________
3. ________
4. ________
5. ________
6. ________
7. ________
8. ________
9. ________
10. ________
11. ________
12. ________
13. ________
14. ________

## INSTRUCTIONS FOR RANKING 3

Rank the decisions according to their urgency. Define urgency as referring to the speed with which the decision has to be made once you know it must be made.

<u>INSTRUCTIONS</u>: Enter the two-letter codes fir the decisions below in the order in which you ranked them. That is, write the code for the decision you ranked first next to '1.', for the decision you ranked second next to '2.' and so on.

1. ________
2. ________
3. ________
4. ________
5. ________
6. ________
7. ________
8. ________
9. ________
10. ________
11. ________
12. ________
13. ________
14. ________

INSTRUCTIONS FOR RANKING 4

Rank these decisions according to your workload during each of them. Consider both your cognitive, or mental workload and your physical workload in ranking the deicisons. Rank the decision during which your workload is heaviest first, and the one during which your workload is least heavy last.

INSTRUCTIONS: Enter the two-letter codes fir the decisions below in the order in which you ranked them. That is, write the code for the decision you ranked first next to '1.', for the decision you ranked second next to '2.' and so on.

1. ________
2. ________
3. ________
4. ________
5. ________
6. ________
7. ________
8. ________
9. ________
10. ________
11. ________
12. ________
13. ________
14. ________

# APPENDIX C

## RESULTS OF UNCONSTRAINED SORTINGS OF ASW DECISIONS

This appendix presents the results of unconstrained sortings of fourteen air ASW decision by 30 S-3A Tactical Coordinators (TACCO's) stationed at NAS Cecil Field, Florida. The sortings were performed as part of interviews conducted between 10 December 1979 and 13 December 1979. The interview procedure is described in Chapter 3.

The fourteen decisions that were sorted are shown in Table XVI. The instructions for the sorting task, and a sample of the form on which the results were recorded, are given in Appendix B.

Each sorting presented as several lists of decisions. In this task, each decision function is identified only by a two-letter code. The code used for each decision is also given in Table XVI.

Table XVI. Fourteen ASW Decision Function and Alphabetic Codes

| CODE | DECISION FUNCTION |
|---|---|
| AP | ADJUST PATTERN TO SENSOR FAILURE |
| EP | EXTEND SENSOR PATTERN |
| AM | ANTICIPATE TARGET MOVEMENT |
| MP | CONSTRUCT SENSOR MONITORING PATTERN |
| CH | COORDINATE HAND-OFF |
| VC | DETERMINE SIGNAL IS VALID CONTACT |
| DS | DETERMINE WEAPON AND SETTING FOR ATTACK |
| AC | GAIN ATTACK CRITERIA |
| TF | DETERMINE TARGET FIX |
| CP | CREATE SENSOR PATTERN |
| ME | MANAGE EQUIPMENT/STORES TO ACCOMODATE PRESENT AND FUTURE NEEDS |
| CS | CLASSIFY SIGNAL |
| PC | COMPENSATE FOR IN SITU ACOUSTICAL AND ATMOSPHERIC PROPAGATION CONDITIONS |
| LP | DETERMINE AIRCRAFT LAUNCH POSITION FOR ATTACK ON TARGET |

SUBJECT 1

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | ME |
| 2 | CP,MP,PC,AP,EP |
| 3 | VC,CS |
| 4 | TF,AM,AC |
| 5 | DS,LP |
| 6 | CH |

SUBJECT 2

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,PC,MP,ME |
| 2 | EP,AP |
| 3 | VC,CS |
| 4 | TF,AM |
| 5 | AC,LP,DS |
| 6 | CH |

SUBJECT 3

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,ME,AP,MP |
| 2 | EP,PC |
| 3 | VC,CS |
| 4 | TF,AM |
| 5 | AC,DS,LP |
| 6 | CH |

SUBJECT 4

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,MP,EP |
| 2 | PC,ME,AP |
| 3 | VC,CS,TF |
| 4 | AM |
| 5 | DS,LP,AC |
| 6 | CH |

SUBJECT 5

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | AM,CP,MP |
| 2 | PC,AP,ME,EP |
| 3 | VC,CS,TF |
| 4 | AC,DS,LP |
| 5 | CH |

SUBJECT 6

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,PC,MP,EP |
| 2 | ME,AP |
| 3 | VC,CS,TF |
| 4 | CH |
| 5 | AM,AC,DS,LP |

SUBJECT 7

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | AM,CP,MP,EP,DS |
| 2 | PC |
| 3 | CS,TF,AP |
| 4 | ME |
| 5 | VC |
| 6 | AC,LP |
| 7 | CH |

SUBJECT 8

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,ME,PC,MP,EP,AP |
| 2 | TF,AM,LP,AC |
| 3 | CS,VC |
| 4 | DS |
| 5 | CH |

SUBJECT 9

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | PC,MP,CP,AP,EP |
| 2 | LP,AC,DS |
| 3 | CS,VC |
| 4 | DS |
| 5 | CH |

SUBJECT 10

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | TF,AM,LP,DS,AC |
| 2 | PC,VC,CS |
| 3 | MP,AP,ME |
| 4 | CP,EP |
| 5 | CH |

SUBJECT 11

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,MP,EP,PC,AP |
| 2 | DS,AC,LP |
| 3 | VC,CS |
| 4 | TF,AM |
| 5 | ME |
| 6 | CH |

SUBJECT 12

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CS,VC |
| 2 | AC,DS,LP |
| 3 | MP,PC,ME,AP |
| 4 | TF,AM |
| 5 | CH |
| 6 | CP,EP |

SUBJECT 13

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CS,VC |
| 2 | DS,LP,AM,TF,AC |
| 3 | CH |
| 4 | AP,EP,MP,PC,CP |
| 5 | ME |

SUBJECT 14

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | AC,AM,DS,TF |
| 2 | CP,EP,AP |
| 3 | MP,LP |
| 4 | VC,PC |
| 5 | CS |
| 6 | ME |
| 7 | CH |

SUBJECT 15

| GROUP | DECISION FUNCTION IN GROUP |
|---|---|
| 1 | CP,PC,MP,ME,EP,AP |
| 2 | LP,AM,TF,AC |
| 3 | CS,VC |
| 4 | DS |
| 5 | CH |

SUBJECT 16

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | PC,CP,AP,MP,EP |
| 2 | LP,DS,AC,AM |
| 3 | CS,VC,TF |
| 4 | ME |
| 5 | CH |

SUBJECT 17

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | ME,AP,DS,CH |
| 2 | PC,CP,AM,TF,AC |
| 3 | MP,EP |
| 4 | CS,VC |
| 5 | CH |

SUBJECT 18

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | AP,EP,MP,PC,CP |
| 2 | DS,LP,AM,TF,AC |
| 3 | CS,VC |
| 4 | CH |
| 5 | ME |

SUBJECT 19

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,PC,MP,EP |
| 2 | AM,AC,DS,LP |
| 3 | ME,AP |
| 4 | VC,CS,TF |
| 5 | CH |

SUBJECT 20

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,EP |
| 2 | MP,PC,ME,AP |
| 3 | AC,DS,LP |
| 4 | TF,AM |
| 5 | CS,VC |
| 6 | CH |

SUBJECT 21

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,MP,EP,PC,AP |
| 2 | DS,AC,LP |
| 3 | TF,AM |
| 4 | ME |
| 5 | VC,CS |
| 6 | CH |

SUBJECT 22

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | PC,ME,AP |
| 2 | CP,MP,EP |
| 3 | VC,CS,TF |
| 4 | DS,LP,AC |
| 5 | AM |
| 6 | CH |

SUBJECT 23

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | AC,DS,LP,AM,TF |
| 2 | MP,AP,ME |
| 3 | PC,VC,CS |
| 4 | CP,EP |
| 5 | CH |

SUBJECT 24

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | AC,DS,LP |
| 2 | CP,ME,AP,MP |
| 3 | EP,PC |
| 4 | TF,AM |
| 5 | VC,CS |
| 6 | CH |

SUBJECT 25

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | PC,MP,CP,EP,AP |
| 2 | LP,AC,DS |
| 3 | ME |
| 4 | VC,CS |
| 5 | AM,TF |
| 6 | CH |

SUBJECT 26

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | ME,MP,PC,CP |
| 2 | AC,LP,DS |
| 3 | EP,AP |
| 4 | VC,CS |
| 5 | TF,AM |
| 6 | CH |

SUBJECT 27

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | AP,EP,MP,PC,ME,CP |
| 2 | AC,LP,AM,TF |
| 3 | VC,CS |
| 4 | DS |
| 5 | CH |

SUBJECT 28

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,MP,PC,EP,AP |
| 2 | TF,AM,AC |
| 3 | ME |
| 4 | CS,VC |
| 5 | LP,DS |
| 6 | CH |

SUBJECT 29

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,ME,EP,TF,AM,AP,LP,MP |
| 2 | VC,CS |
| 3 | PC |
| 4 | DS |
| 5 | AC |
| 6 | CH |

SUBJECT 30

| GROUP | DECISION FUNCTIONS IN GROUP |
|---|---|
| 1 | CP,ME,AP,MP |
| 2 | DS,LP,AC |
| 3 | VC,CS |
| 4 | TF,AM |
| 5 | PC,EP |
| 6 | CH |

# APPENDIX D

## RESULTS OF RANKINGS OF ASW DECISIONS

This appendix presents the results of rankings of fourteen Air ASW decisions (listed in Table XVI) by 30 TACCOs from NAS Cecil Field. These rankings were performed as part of the interview described in Chapter 3. The fourteen decisions were ranked according to four different criteria. The instructions for these rankings and the forms on which the results were recorded are given in Appendix B. The first ranking was done according to the perceived 'importance' of the decision in a mission where the objective is to 'attack' and destroy the hostile submarine. The second ranking was done according to the perceived 'importance' of the decision function in a mission where the objective is to survey the submarine only. The third rankign was done according to the preceived 'urgency' of the decisions in whatever type of mission gave then the greatest urgency. The fourth ranking was done according to the TACCO's perceived 'workload' (both cognitive and physical) during each of the fourteen decision functions.

The results of these four rankings are given below. The ranking generates by each individual using each criteria is presented as a list of the two-letter codes used in the interviews to represent the decision functions. Table XVI (Appendix C) contains the full decision name represented by each two-letter code. The order in which the individuals are listed is arbitrary, but is the same for all four rankings.

RANKING 1

CRITERION: IMPORTANCE TO MISSION WITH ATTACK ON SUBMARINE

SUBJECT NUMBER — DECISION FUNCTION (RANKING GIVEN)

| SUBJECT NUMBER | AP | EP | AM | MP | CH | VC | DS | AC | TF | CP | ME | CS | PC | CP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 7 | 8 | 2 | 5 | 13 | 9 | 11 | 3 | 1 | 4 | 14 | 10 | 6 | 12 |
| 2 | 13 | 10 | 4 | 11 | 6 | 8 | 2 | 1 | 5 | 14 | 9 | 7 | 12 | 3 |
| 3 | 6 | 5 | 10 | 3 | 14 | 7 | 13 | 11 | 9 | 1 | 4 | 8 | 2 | 12 |
| 4 | 12 | 13 | 7 | 8 | 14 | 4 | 2 | 1 | 6 | 10 | 11 | 5 | 9 | 3 |
| 5 | 9 | 12 | 8 | 13 | 14 | 2 | 4 | 1 | 7 | 11 | 10 | 3 | 6 | 5 |
| 6 | 11 | 12 | 1 | 4 | 14 | 5 | 9 | 8 | 7 | 3 | 13 | 6 | 2 | 10 |
| 7 | 11 | 6 | 2 | 7 | 13 | 8 | 4 | 1 | 5 | 10 | 14 | 9 | 12 | 3 |
| 8 | 12 | 6 | 2 | 3 | 14 | 8 | 4 | 10 | 9 | 1 | 13 | 7 | 5 | 11 |
| 9 | 13 | 12 | 5 | 11 | 14 | 10 | 4 | 1 | 3 | 7 | 8 | 9 | 6 | 2 |
| 10 | 10 | 13 | 6 | 12 | 14 | 2 | 11 | 5 | 4 | 3 | 7 | 1 | 8 | 9 |
| 11 | 9 | 12 | 15 | 8 | 13 | 7 | 3 | 2 | 4 | 11 | 14 | 6 | 10 | 1 |
| 12 | 8 | 11 | 6 | 12 | 13 | 10 | 7 | 4 | 3 | 2 | 9 | 1 | 14 | 5 |
| 13 | 13 | 9 | 6 | 10 | 14 | 12 | 3 | 4 | 5 | 7 | 11 | 1 | 8 | 2 |
| 14 | 13 | 10 | 6 | 9 | 14 | 2 | 4 | 8 | 7 | 1 | 12 | 3 | 11 | 5 |
| 15 | 9 | 11 | 5 | 3 | 13 | 4 | 7 | 8 | 6 | 2 | 14 | 1 | 12 | 10 |
| 16 | 11 | 12 | 6 | 9 | 14 | 8 | 4 | 2 | 3 | 7 | 13 | 5 | 10 | 1 |
| 17 | 9 | 7 | 8 | 10 | 14 | 13 | 11 | 1 | 5 | 3 | 6 | 12 | 4 | 2 |
| 18 | 11 | 9 | 10 | 5 | 13 | 12 | 4 | 3 | 6 | 1 | 14 | 8 | 7 | 2 |
| 19 | 9 | 11 | 7 | 8 | 14 | 6 | 2 | 4 | 5 | 12 | 13 | 1 | 10 | 3 |
| 20 | 12 | 11 | 7 | 9 | 14 | 1 | 5 | 4 | 3 | 10 | 13 | 2 | 8 | 6 |
| 21 | 11 | 12 | 4 | 10 | 14 | 2 | 8 | 3 | 7 | 5 | 13 | 1 | 6 | 9 |
| 22 | 12 | 13 | 8 | 10 | 14 | 2 | 6 | 5 | 4 | 9 | 1 | 3 | 11 | 7 |
| 23 | 13 | 12 | 8 | 10 | 14 | 4 | 6 | 2 | 5 | 7 | 11 | 3 | 9 | 1 |
| 24 | 14 | 10 | 5 | 12 | 6 | 2 | 8 | 4 | 3 | 11 | 13 | 1 | 7 | 9 |
| 25 | 10 | 11 | 8 | 9 | 14 | 13 | 3 | 1 | 7 | 5 | 4 | 6 | 12 | 2 |
| 26 | 6 | 7 | 12 | 10 | 14 | 13 | 3 | 2 | 9 | 5 | 8 | 1 | 11 | 4 |
| 27 | 11 | 12 | 13 | 3 | 14 | 6 | 9 | 8 | 7 | 2 | 4 | 5 | 1 | 10 |
| 28 | 12 | 10 | 7 | 11 | 4 | 2 | 9 | 3 | 6 | 13 | 8 | 1 | 14 | 5 |
| 29 | 12 | 7 | 4 | 14 | 9 | 1 | 6 | 3 | 5 | 11 | 13 | 12 | 10 | 8 |
| 30 | 8 | 7 | 4 | 11 | 5 | 14 | 2 | 3 | 6 | 10 | 9 | 13 | 12 | 1 |

RANKING 2

CRITERION: IMPORTANCE TO MISSION WITH TRACKING OF SUBMARINE BUT NO ATTACK

| SUBJECT NUMBER | DECISION FUNCTION (RANKING GIVEN) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AP | EP | AM | MP | CH | VC | DS | AC | TF | CP | ME | CS | PC | CP |
| 1 | 4 | 5 | 9 | 2 | 10 | 6 | 14 | 12 | 8 | 1 | 11 | 7 | 3 | 13 |
| 2 | 11 | 8 | 2 | 9 | 4 | 6 | 14 | 1 | 3 | 12 | 7 | 5 | 10 | 13 |
| 3 | 6 | 5 | 10 | 3 | 11 | 7 | 14 | 12 | 9 | 1 | 4 | 8 | 2 | 13 |
| 4 | 9 | 10 | 2 | 8 | 3 | 4 | 13 | 12 | 1 | 7 | 11 | 6 | 5 | 14 |
| 5 | 7 | 10 | 5 | 11 | 6 | 1 | 12 | 14 | 4 | 9 | 8 | 2 | 3 | 13 |
| 6 | 9 | 8 | 1 | 4 | 10 | 5 | 13 | 12 | 7 | 3 | 11 | 6 | 2 | 14 |
| 7 | 7 | 8 | 11 | 2 | 4 | 5 | 14 | 12 | 9 | 1 | 10 | 6 | 3 | 13 |
| 8 | 11 | 5 | 2 | 3 | 9 | 7 | 13 | 14 | 8 | 1 | 10 | 6 | 4 | 12 |
| 9 | 11 | 8 | 2 | 9 | 7 | 6 | 14 | 13 | 1 | 10 | 3 | 5 | 4 | 12 |
| 10 | 9 | 11 | 8 | 10 | 5 | 2 | 14 | 12 | 4 | 3 | 6 | 1 | 7 | 13 |
| 11 | 7 | 10 | 2 | 6 | 1 | 5 | 13 | 12 | 3 | 9 | 11 | 4 | 8 | 14 |
| 12 | 12 | 9 | 5 | 10 | 6 | 11 | 14 | 4 | 3 | 2 | 7 | 1 | 8 | 13 |
| 13 | 7 | 11 | 4 | 10 | 2 | 12 | 14 | 3 | 5 | 9 | 6 | 1 | 8 | 13 |
| 14 | 11 | 8 | 5 | 7 | 4 | 2 | 14 | 12 | 6 | 1 | 10 | 3 | 9 | 13 |
| 15 | 11 | 13 | 6 | 4 | 9 | 3 | 8 | 7 | 5 | 1 | 14 | 2 | 12 | 10 |
| 16 | 10 | 9 | 2 | 8 | 3 | 5 | 14 | 12 | 1 | 7 | 11 | 4 | 6 | 13 |
| 17 | 7 | 4 | 5 | 6 | 10 | 11 | 14 | 8 | 9 | 1 | 2 | 12 | 3 | 13 |
| 18 | 7 | 6 | 9 | 2 | 11 | 4 | 14 | 13 | 10 | 1 | 8 | 5 | 3 | 12 |
| 19 | 12 | 8 | 4 | 6 | 1 | 3 | 14 | 13 | 5 | 10 | 9 | 2 | 7 | 11 |
| 20 | 10 | 9 | 4 | 7 | 5 | 1 | 14 | 12 | 3 | 8 | 11 | 2 | 6 | 13 |
| 21 | 12 | 13 | 5 | 11 | 4 | 2 | 9 | 3 | 8 | 6 | 14 | 1 | 7 | 10 |
| 22 | 9 | 10 | 5 | 7 | 11 | 2 | 13 | 12 | 4 | 6 | 1 | 3 | 8 | 14 |
| 23 | 8 | 13 | 3 | 14 | 5 | 4 | 10 | 9 | 2 | 7 | 6 | 1 | 12 | 11 |
| 24 | 11 | 8 | 4 | 10 | 5 | 2 | 13 | 12 | 3 | 9 | 7 | 1 | 6 | 14 |
| 25 | 9 | 8 | 6 | 7 | 1 | 11 | 13 | 12 | 5 | 3 | 2 | 4 | 10 | 14 |
| 26 | 6 | 7 | 3 | 9 | 4 | 10 | 13 | 12 | 2 | 5 | 8 | 1 | 11 | 14 |
| 27 | 7 | 10 | 9 | 3 | 8 | 6 | 14 | 12 | 11 | 2 | 4 | 5 | 1 | 13 |
| 28 | 7 | 6 | 5 | 10 | 3 | 2 | 13 | 12 | 11 | 8 | 4 | 1 | 9 | 14 |
| 29 | 9 | 6 | 3 | 11 | 5 | 1 | 13 | 12 | 4 | 8 | 10 | 2 | 7 | 14 |
| 30 | 6 | 5 | 2 | 8 | 3 | 9 | 13 | 12 | 4 | 1 | 7 | 10 | 11 | 14 |

RANKING 3

CRITERION: URGENCY OF THE DECISION FUNCTION WITHIN A MISSION

| SUBJECT NUMBER | DECISION FUNCTION (RANKING GIVEN) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AP | EP | AM | MP | CH | VC | DS | AC | TF | CP | ME | CS | PC | LP |
| 1 | 12 | 8 | 4 | 10 | 14 | 1 | 6 | 5 | 3 | 9 | 13 | 2 | 11 | 7 |
| 2 | 9 | 8 | 5 | 13 | 6 | 4 | 2 | 3 | 7 | 14 | 11 | 10 | 12 | 1 |
| 3 | 11 | 9 | 3 | 13 | 14 | 7 | 2 | 5 | 4 | 12 | 10 | 6 | 8 | 1 |
| 4 | 9 | 8 | 4 | 10 | 14 | 1 | 7 | 5 | 3 | 11 | 12 | 2 | 13 | 6 |
| 5 | 7 | 11 | 10 | 13 | 8 | 4 | 3 | 1 | 9 | 14 | 12 | 5 | 6 | 2 |
| 6 | 4 | 5 | 3 | 13 | 9 | 10 | 6 | 7 | 2 | 14 | 12 | 11 | 8 | 1 |
| 7 | 6 | 7 | 4 | 11 | 14 | 8 | 2 | 3 | 5 | 12 | 13 | 9 | 10 | 1 |
| 8 | 8 | 7 | 4 | 13 | 14 | 9 | 3 | 2 | 6 | 12 | 5 | 10 | 11 | 1 |
| 9 | 1 | 9 | 12 | 11 | 14 | 4 | 7 | 6 | 5 | 13 | 8 | 3 | 10 | 2 |
| 10 | 3 | 9 | 6 | 14 | 13 | 11 | 12 | 1 | 7 | 5 | 4 | 10 | 8 | 2 |
| 11 | 7 | 13 | 4 | 14 | 10 | 1 | 3 | 8 | 9 | 2 | 5 | 11 | 6 | 12 |
| 12 | 9 | 12 | 2 | 8 | 13 | 5 | 7 | 1 | 3 | 11 | 14 | 4 | 10 | 6 |
| 13 | 12 | 11 | 5 | 13 | 9 | 4 | 3 | 1 | 7 | 14 | 8 | 6 | 10 | 2 |
| 14 | 6 | 12 | 4 | 11 | 14 | 8 | 5 | 2 | 3 | 13 | 7 | 9 | 10 | 1 |
| 15 | 11 | 10 | 5 | 13 | 9 | 6 | 2 | 1 | 4 | 12 | 8 | 7 | 14 | 3 |
| 16 | 12 | 11 | 3 | 9 | 14 | 2 | 13 | 4 | 7 | 8 | 10 | 1 | 6 | 5 |
| 17 | 12 | 14 | 8 | 13 | 11 | 10 | 3 | 1 | 6 | 7 | 5 | 9 | 4 | 2 |
| 18 | 8 | 9 | 7 | 10 | 12 | 13 | 4 | 2 | 3 | 11 | 5 | 14 | 6 | 1 |
| 19 | 6 | 9 | 5 | 13 | 11 | 7 | 4 | 2 | 3 | 14 | 10 | 8 | 12 | 1 |
| 20 | 12 | 10 | 6 | 11 | 14 | 4 | 7 | 1 | 5 | 8 | 13 | 3 | 9 | 2 |
| 21 | 7 | 10 | 5 | 9 | 13 | 11 | 2 | 1 | 4 | 8 | 14 | 12 | 6 | 3 |
| 22 | 7 | 14 | 5 | 12 | 13 | 3 | 8 | 1 | 4 | 11 | 9 | 6 | 10 | 2 |
| 23 | 13 | 14 | 7 | 10 | 12 | 4 | 3 | 2 | 6 | 11 | 8 | 5 | 9 | 1 |
| 24 | 8 | 13 | 7 | 14 | 12 | 4 | 3 | 2 | 6 | 9 | 11 | 5 | 10 | 1 |
| 25 | 1 | 13 | 3 | 14 | 11 | 7 | 9 | 5 | 4 | 12 | 8 | 10 | 6 | 2 |
| 26 | 14 | 12 | 4 | 13 | 8 | 2 | 9 | 6 | 3 | 11 | 7 | 1 | 10 | 5 |
| 27 | 9 | 12 | 4 | 11 | 8 | 5 | 3 | 1 | 7 | 14 | 10 | 6 | 13 | 2 |
| 28 | 10 | 9 | 3 | 13 | 6 | 4 | 2 | 5 | 11 | 14 | 8 | 7 | 12 | 1 |
| 29 | 12 | 8 | 4 | 13 | 11 | 9 | 2 | 3 | 5 | 6 | 7 | 10 | 14 | 1 |
| 30 | 6 | 11 | 12 | 13 | 10 | 5 | 2 | 1 | 9 | 8 | 14 | 4 | 7 | 3 |

## RANKING 4

CRITERION: WORKLOAD OF TACCO DURING DECISION FUNCTION

| SUBJECT NUMBER | DECISION FUNCTION (RANKING GIVEN) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AP | EP | AM | MP | CH | VC | DS | AC | TF | CP | ME | CS | PC | LP |
| 1 | 6 | 7 | 2 | 8 | 14 | 12 | 4 | 3 | 1 | 9 | 11 | 13 | 10 | 5 |
| 2 | 8 | 9 | 1 | 13 | 4 | 11 | 6 | 3 | 2 | 14 | 7 | 10 | 12 | 5 |
| 3 | 10 | 4 | 6 | 11 | 14 | 12 | 9 | 7 | 5 | 1 | 3 | 13 | 2 | 8 |
| 4 | 11 | 9 | 4 | 13 | 14 | 7 | 5 | 1 | 3 | 8 | 12 | 6 | 10 | 2 |
| 5 | 4 | 5 | 7 | 2 | 8 | 10 | 13 | 14 | 6 | 1 | 3 | 9 | 11 | 12 |
| 6 | 9 | 10 | 2 | 14 | 6 | 8 | 4 | 5 | 1 | 13 | 12 | 7 | 11 | 3 |
| 7 | 7 | 6 | 9 | 3 | 13 | 4 | 11 | 10 | 8 | 1 | 14 | 5 | 2 | 12 |
| 8 | 7 | 5 | 3 | 13 | 8 | 11 | 2 | 1 | 6 | 14 | 12 | 10 | 9 | 4 |
| 9 | 2 | 4 | 9 | 8 | 7 | 12 | 11 | 1 | 6 | 5 | 10 | 13 | 3 | 14 |
| 10 | 9 | 10 | 6 | 8 | 4 | 12 | 14 | 3 | 5 | 2 | 1 | 13 | 7 | 11 |
| 11 | 14 | 4 | 2 | 12 | 13 | 8 | 11 | 6 | 5 | 3 | 1 | 7 | 9 | 10 |
| 12 | 13 | 2 | 9 | 12 | 8 | 10 | 5 | 3 | 6 | 1 | 7 | 11 | 14 | 4 |
| 13 | 5 | 6 | 12 | 11 | 4 | 7 | 1 | 3 | 9 | 10 | 14 | 8 | 13 | 2 |
| 14 | 10 | 9 | 2 | 8 | 5 | 12 | 7 | 4 | 3 | 1 | 14 | 13 | 11 | 6 |
| 15 | 4 | 5 | 8 | 13 | 9 | 12 | 1 | 6 | 10 | 14 | 3 | 11 | 7 | 2 |
| 16 | 6 | 7 | 3 | 8 | 14 | 13 | 10 | 4 | 2 | 9 | 1 | 12 | 11 | 5 |
| 17 | 14 | 12 | 4 | 13 | 6 | 9 | 2 | 3 | 5 | 10 | 7 | 8 | 11 | 1 |
| 18 | 10 | 9 | 4 | 7 | 2 | 12 | 14 | 8 | 3 | 6 | 1 | 11 | 5 | 13 |
| 19 | 10 | 12 | 5 | 11 | 4 | 8 | 3 | 1 | 6 | 14 | 9 | 7 | 13 | 2 |
| 20 | 7 | 11 | 5 | 13 | 1 | 6 | 2 | 4 | 9 | 14 | 8 | 10 | 12 | 3 |
| 21 | 12 | 9 | 1 | 13 | 14 | 6 | 4 | 2 | 3 | 8 | 10 | 7 | 11 | 5 |
| 22 | 11 | 9 | 7 | 10 | 1 | 13 | 3 | 2 | 4 | 8 | 14 | 12 | 5 | 6 |
| 23 | 11 | 12 | 6 | 10 | 1 | 13 | 7 | 5 | 8 | 2 | 3 | 14 | 9 | 4 |
| 24 | 4 | 5 | 6 | 11 | 9 | 13 | 3 | 2 | 7 | 8 | 10 | 12 | 14 | 1 |
| 25 | 8 | 9 | 5 | 11 | 7 | 13 | 4 | 2 | 1 | 10 | 6 | 12 | 14 | 3 |
| 26 | 9 | 10 | 7 | 11 | 3 | 13 | 6 | 1 | 5 | 12 | 2 | 14 | 8 | 4 |
| 27 | 11 | 12 | 10 | 9 | 8 | 13 | 6 | 7 | 4 | 1 | 3 | 14 | 2 | 5 |
| 28 | 5 | 13 | 6 | 9 | 4 | 8 | 12 | 1 | 3 | 11 | 14 | 7 | 10 | 2 |
| 29 | 14 | 8 | 3 | 11 | 4 | 9 | 13 | 12 | 1 | 2 | 6 | 7 | 5 | 10 |
| 30 | 8 | 11 | 6 | 9 | 1 | 13 | 2 | 4 | 5 | 7 | 10 | 14 | 12 | 3 |

## APPENDIX E

PLOTS ON DECISION FUNCTIONS FROM THREE DIMENSIONS
(FROM ZACHARY 1980b)

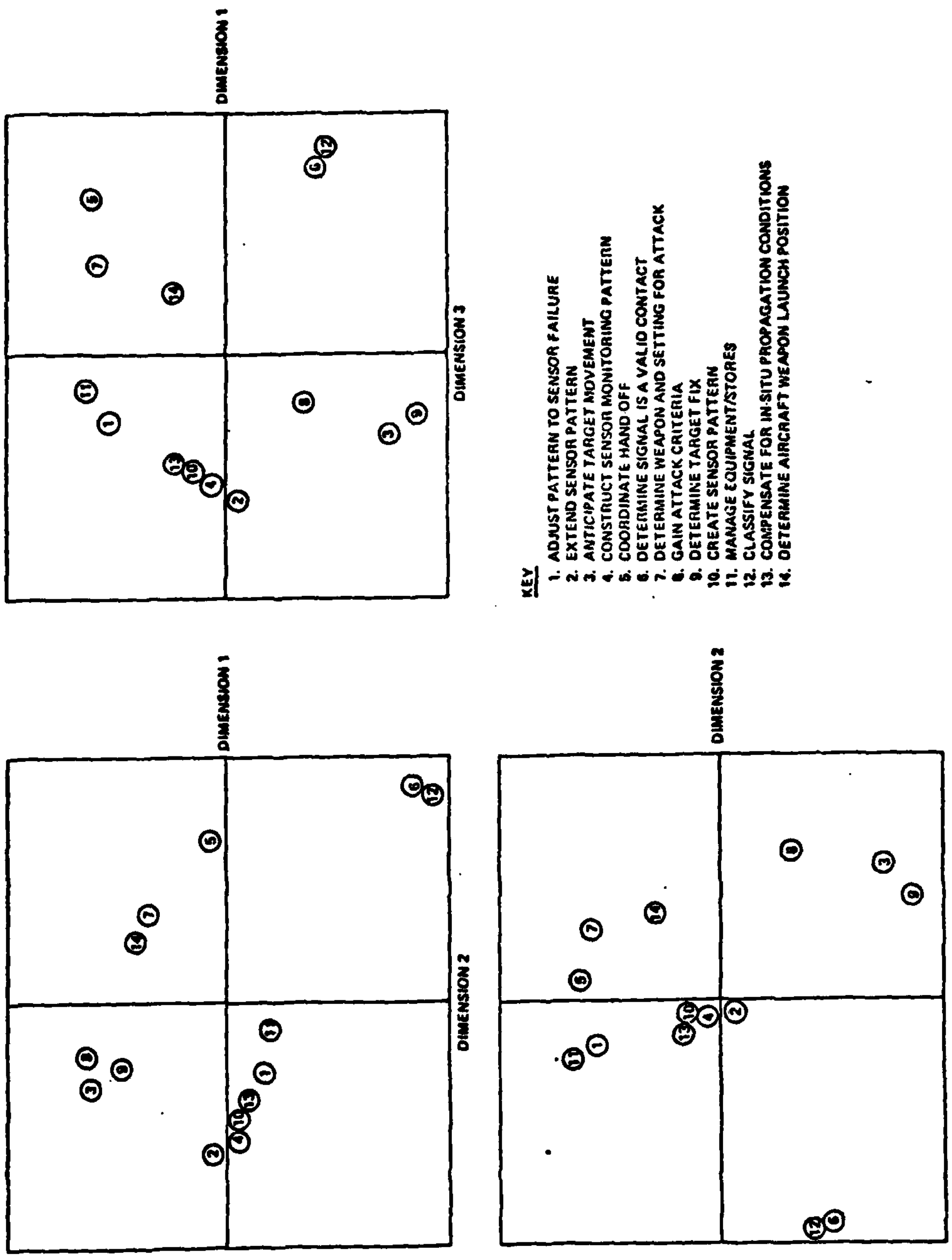


Figure 14. Plots of Decision Functions on Three Dimensions (from Zachary 1980b)

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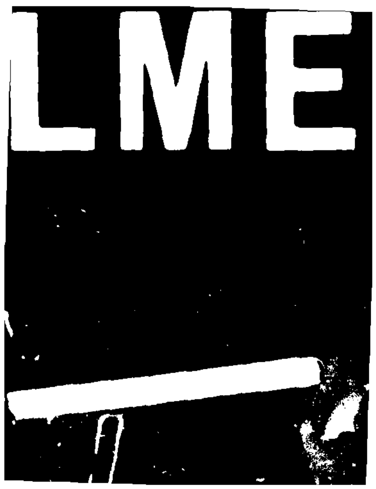
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